Modeling Causes and Impacts of Greenhouse Gas Emission in a City

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Abstract

Global warming is one of the most significant issues that humans face in today's world. Even small changes in the earth's average temperatures can increase severe weather events such as storms, floods and droughts, change in ecosystem, adverse impact on health and lives of human and other species. Global warming is caused by increasing concentration of greenhouse gases (GHG) in atmosphere, and cities are major contributors of greenhouse gas emission. All cities have a responsibility and a role to play in controlling the GHG emission, confronting climate change and its potential impacts. We develop a system dynamics model that can help cities better understand the causes and impacts of GHG emission within various subsystems of cities, and formulate and test effective policies for controlling the GHG emission.

1 Introduction

Global warming caused by increasing concentration of greenhouse gases (GHG) in atmosphere is one of the most significant issues that humans face in today's world, and it is already impacting our lives. There is broad consensus within the scientific community that even small changes in the earth's average temperatures can increase severe weather events such as storms, floods and droughts, change in ecosystem, adverse impact on health and lives of human and other species. Greenhouse gases including water vapor, carbon dioxide, methane, chlorofluorocarbon, tropospheric (ground level) ozone, and nitrous oxide, create a greenhouse effect by trapping heat near earth's surface, and concentrations of many of these gases are increasing in the atmosphere (Silver & DeFries, 1991). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the principal greenhouse gases emitted to the atmosphere from the burning of fossil fuels to produce heat and electricity. Of these three GHGs, CO_2 represents more than 99% of the total greenhouse gas emissions from fuels combusted by commercial, industrial, and electricity production sources, with CH_4 and N_2O together representing less than 1% from the same sources (EPA ESPM, 2009).

Cities are where people and buildings are concentrated, and they are major contributors of GHG emission. For instance, in 2005 New York City's total greenhouse gas emissions were 58.3 million metric tons of carbon dioxide equivalent (mt CO_2e), a common unit that sums up emission of different greenhouse gases with different weights according to their relative contribution to global climate change. Of these, 79 percent were caused by the consumption of energy by buildings in the city, in contrast to the national average of 34 percent. For example, the global warming potential (GWP) of CH_4 and N_2O are 21 and 310 relative to CO_2 respectively (EPA ESPM, 2009). Major cities such as the New York City are aware of the direct effects of global climate change, including increased temperatures, rising sea levels, higher risks of severe floods and storms (NYC GHG Emission, 2007). All cities have a responsibility and a role to play in controlling the GHG emission, confronting climate change and its potential impacts. For example, New York City's government is committed to reducing the city's CO_2 emissions by 30 percent below 2005 levels by 2030 through an initiative called PlaNYC, and making the city cleaner, greener and healthier (PlaNYC, 2007)

New York City reports the potential impacts of GHG emission (therefore, climate change) as follows (NYC GHG Emission, 2007):

- Public Health and Air Quality
  - Higher temperatures and increased frequency of heat waves may increase the number of heat-related deaths and the incidence of heat-related illnesses. Higher temperatures may expand the habitat and infectivity of disease-carrying insects increasing the risk to humans. Ground level ozone is produced when higher temperatures and strong sunlight react with hydrocarbons and nitrogen oxides (NOx), worsening air pollution and potentially exacerbating respiratory illnesses such as asthma.
- Coastal Areas
  - Along much of the New York coast, sea level is expected to rise significantly with increases in temperature. Such a rise in sea level can lead to flooding, loss of coastal wetlands, erosion of beaches, and saltwater intrusion into lakes and rivers, and will likely increase the vulnerability of coastal areas to storms and other severe weather patterns.
- Water Supply
  - The city's water system could be affected by increased evaporation of water due to warmer temperatures, which would reduce river flows and lower lake and reservoir levels, particularly in summer when demand for water is at its highest. Higher temperatures and more violent storms could lead to increased turbidity of reservoirs.
- Energy Demands
  - A warmer climate increases the total demand for electricity, because the increase in demand for summer cooling is expected to outweigh the decrease in winter warming needs. With a warming climate, the urban heat island effect (the absorption of heat by buildings during daylight hours and the radiation of the heat at night) will become an increasing issue of concern.

In this paper, we study the relationship between GHG emission and other issues of modern cities including air pollution, healthcare, energy, water management and transportation through a System Dynamics (SD) modeling of simplified view of GHG emission in a city. Our goal is to develop a system dynamics model that can help cities better understand the causes and impacts of GHG emission within various subsystems of cities, and formulate and test effective policies for controlling the GHG emission. We develop and calibrate a SD model using published emission data from the New York City (NYC GHG Emission, 2007), and examine dynamic effects of GHG emission and investment of GHG reduction initiatives.

2 SD Model Description of GHG Emission

The GHG emission SD model is developed using a system dynamics modeling tool, Vensim (Ventana Systems Inc. 1998). Three sources of GHG emission are included in this model: electricity consumption, heating fuel consumption and vehicle combustion as shown in Figure 1. The emission from electricity consumption is indirect emission, which is generated mostly by combustion of fossil fuels to generate electricity that is used to light and cool buildings, light street light, run equipment such as computers, and power industrial facilities. The emission for heating fuel and vehicle combustion are direct emission, which is generated by burning primary fuel such as natural gas, fuel oil and gasoline. As agriculture is virtually nonexistent in New York City, methane and nitrous oxide emissions, which are often significant when measuring emissions in other geographic areas or on a larger scale, are not included in this model as also indicated by NYC report (PlaNYC, 2007).

In our model, electricity consumption accumulates based on the rate of electricity demand increase, which depends on demand increase of electricity, electricity consumption efficiency increase and additional electricity demand due to high temperature (global warming). When there is no increase of electricity demand, no electricity consumption efficiency and no additional electricity demand due to high temperature, there is no net increase of electricity consumption. The mathematical expression representing the demand for electricity at time, t, is provided in Equation (1).

$$D_E(t) = \int_0^t R_E d\tau + D_E(0) \tag{1}$$

where $D_E(t)$ = electricity consumption (demand) at time t,

$D_E(0)$ = electricity consumption (demand) at time $t=0$,

R_E = increase of electricity demand = $D_E[(1+EDI)(1-EEI)(1+AED)-1)]$

EDI = electricity demand increase (yearly)

EEI = electricity consumption efficiency increase (yearly)

AED = additional electricity demand due to high temperature (global warming)

Heating fuel consumption, as shown in Equation 2, accumulates based on the rate of heating fuel demand increase, which depends on demand increase of heating fuel and heating fuel consumption efficiency. When there is no increase of heating fuel demand and no heating fuel consumption efficiency, there would be no net increase of heating fuel consumption

$$D_H(t) = \int_0^t R_H d\tau + D_H(0) \tag{2}$$

where $D_H(t)$ = heating fuel consumption (demand) at time t,

$D_H(0)$ = heating fuel consumption (demand) at time $t=0$,

R_H = increase of heating fuel demand = $D_E[(1+HDI)(1-HEI)-1)]$

HDI = heating fuel demand increase (yearly)

HEI = heating fuel consumption efficiency increase (yearly)

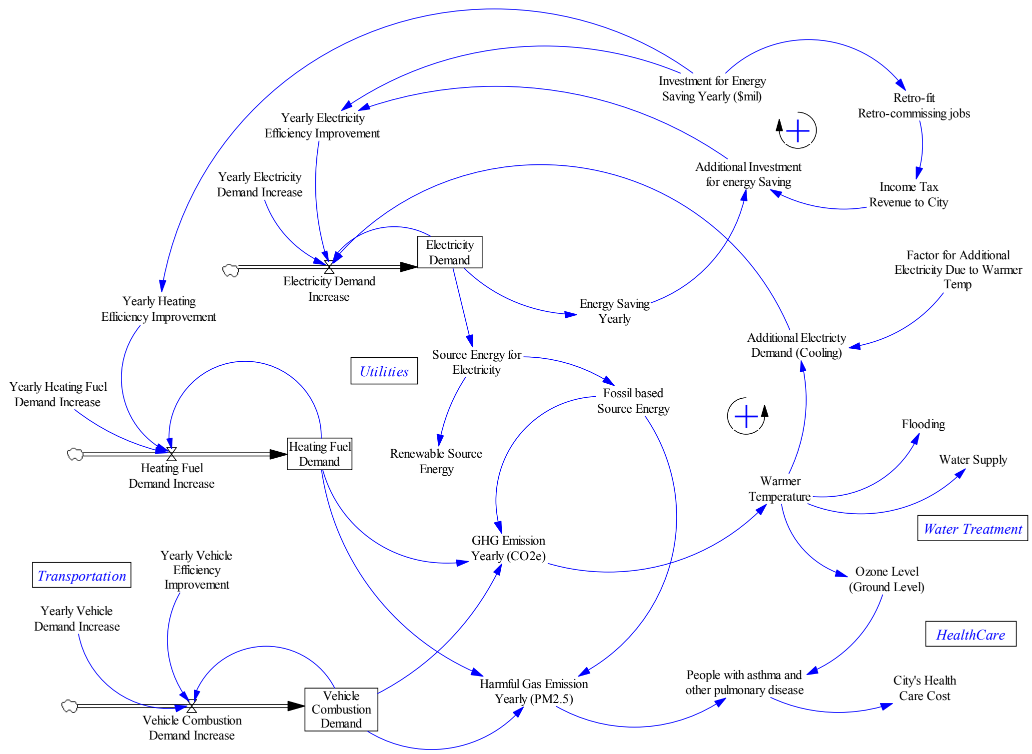

Figure 1: A Simplified Overview of GHG Emission SD Model

Vehicle combustion accumulates based on the rate of vehicle combustion demand increase, which depends on demand increase of vehicle combustion and vehicle combustion efficiency as shown in Equation 3. When there is no increase of heating fuel demand, no heating fuel consumption efficiency and no vehicle combustion efficiency improvement, there would be no net increase of vehicle combustion.

$$D_T(t) = \int_0^t R_T d\tau + D_T(0) \tag{3}$$

where $D_T(t)$ = vehicle combustion (demand) at time t,

$D_T(0)$ = vehicle combustion (demand) at time $t=0$,

R_T = increase of vehicle combustion demand = $D_T\left[(1+VDI)(1-VEI)-1)\right]$

VDI = vehicle combustion demand increase (yearly)

VEI = vehicle combustion consumption efficiency increase (yearly)

Electricity is a secondary energy, which is produced from power plants that burn primary energy such as natural gas, fuel oil or coal or by renewable sources such as solar or wind energy. Power plants that burn primary energy emits GHG and other harmful gases, but energy generation from renewable sources do not emit the gases. Therefore, the electricity consumption is broken into two types of source energy; fossil based energy and renewable energy. For the case of NYC, only 6% of electricity is sourced from renewable energy. The fossil based source energy is multiplied by GHG emission factors to compute the GHG emission in the unit of [kg CO2e/MBtu] or [metric ton (mt) CO2e/MBtu] etc. The fossil based source energy is also multiplied by harmful gas emission factors to compute the harmful gas emission amount. GHG emission factors are numbers that are used to estimate the amount of GHG emission from various electricity GRID and fuel sources, and are available through the U.S. Environmental Protection Agency (eGRID, 2007 & U.S. EPA Climate Leaders Program 2008). Harmful gas emission factors are numbers for estimating the emission amount of those gases from different sources. For example, the GHG emission factors for NYCW (New York City) electricity GRID are 108.40 [kg CO2/MBtu], 0.0048 [kg CH4/MBtu], 0.0007 [kg N2O/MBtu] and 108.7 [kg CO2e/MBtu], and the factors for Fuel Oil (No. 2) are 73.15 [kg CO2/MBtu], 0.0105 [kg CH4/MBtu], 0.00063 [kg N2O/MBtu] and73.57 [kg CO2e/MBtu]. In this model, we use PM 2.5, also known as soot, as a representation of harmful gas emission. PM 2.5 can drift deep into the lungs, where it can cause inflammation and other damage. According to the EPA, high level of the PM 2.5 causes up to 15,000 premature deaths annually. Estimates from the New York City's Department of Health and Mental Hygiene indicates that a 10% decrease of current levels in New York City would result in hundreds fewer deaths annually. PM 2.5 is a by-product of burning fuel in trucks and buses, factories and power plants, and boilers. Other pollutants; sulfur dioxide (SO_2), nitrogen dioxide (NO_X), and volatile organic compounds (VOC), form additional PM 2.5 through chemical reactions (PlaNYC 2007).

Heating fuel is a primary energy, and it also emits GHG and harmful gases. Therefore, heating fuel demand is multiplied by GHG emission factors and harmful gas emission factors to compute its contribution of GHG emission and harmful gas (i.e. PM 2.5) emission respectively. Vehicle combustion also emits GHG and harmful gas. Therefore, vehicle combustion demand is also multiplied by GHG emission factors and harmful gas emission factors to compute its contribution of GHG emission and harmful gas emission respectively. The GHG emission factors and harmful gas emission factors for electricity, heating fuel and vehicle combustion are all different. The overall levels of GHG emission and harmful gas emission are, therefore, the sum of the emission from the three sources; fossil based source energy for electricity consumption, heating fuel consumption and vehicle combustion as shown in Figure 1.

As shown in the right side of Figure 1, GHG emission (i.e. CO_2e level) contributes to warmer average temperature, which increases in turn the total demand for electricity because of the increase of cooling (e.g., extended operations of air conditioners and chillers) in summer, which overrides the decrease in heating (operation of boilers and heaters) in winter. The warmer temperature is expected to increase sea level and also produce severe weather pattern, which can lead to more frequent flooding. The increased evaporation of water due to warmer temperature would reduce river flows and lower lake and reservoir levels. Higher temperature and more violent storm could also lead to contamination and poor quality of drinking water supply. Higher temperature and strong sunlight increase ground level ozone, which can promote respiratory illnesses such as asthma. Harmful gas emission, which includes PM2.5, SO_2, NO_X and VOC, can also make more people sick with the pulmonary diseases, which may increase City's healthcare cost. As shown in the SD model in Figure 1, a city's sub-systems of *utility* and *transportation* are major causes of GHG emission and harmful gas emission, which in turn impact other sub-systems of *water management* and *healthcare*.

In this model, we included two causal loops. One loop captures the impact of GHG emission on warmer temperature, which increases electricity demand for cooling, which in turn increases the overall demand for electricity. More demand of electricity results in greater GHG emissions. Therefore, GHG emission is not just an impact of energy consumption on environment, but also it is a cause for increased energy consumption. Simulation of this causal loop is described in the following section below.

The other causal loop models the effect of investment of energy saving initiatives, which may include energy efficiency improvement initiatives. The initiatives may include various retrofitting and retro-commissioning work such as replacement of energy inefficient HVAC (Heating, Ventilating, and Air Conditioning) equipment for buildings, weatherization of buildings and use of more energy efficient appliances and lighting at homes. The energy saving initiative can also include deployment of smart meters in building and houses so as to condition demand behavior of consumers and reduce the peak energy demand. The investment not only improves energy consumption efficiency and reduces energy consumption, which leads to reduction of GHG emission of harmful gas emission, but also creates additional jobs for retro-fitting and retro-commissioning work, which generate more income tax revenue for a city. The higher revenue would allow a city to invest more money for the energy efficiency and energy saving initiatives. Simulation of this positive causal loop is simulated in the next section too.

3 Simulation Results

The GHG system dynamics model described is simulated for a horizon of 25 years, from year 2005 till 2030. The actual energy consumption of the three mayor types of energy; electricity, heating fuel and vehicle combustion in 2005 and projected energy consumption in a business-as-usual (BAU) scenario in 2030 are summarized in Table 1, which is mostly based on the published information by NYC (PlaNYC 2007). The electricity demand for NYC is expected to increase 44% in 25 years from year 2005 to 2030, and that of heating fuel and vehicle combustion are expected to increase 14% and 30% respectively over the same horizon.

The actual GHG emission level (the total and contributions from three major energy demand categories) and projected emission level in a business-as-usual (BAU) scenario in 2030 are summarized in Table 2. Note that emissions resulting from the decomposition and transportation of solid waste were not included here; therefore, the sum of GHG emission from electricity, heating fuel and vehicle can be greater than the total GHG because methane capture from landfills made solid waste overall a net negative CO2e figure. For the forecasted emission for 2030 compound annual growth rates (CAGR) of 0.95% were used. In 2005, New York City's total greenhouse gas emissions were 58.3 million metric tons of CO_2e. By the year 2030, citywide CO2e emissions are projected to increase by approximately 27% in a business-as-usual (BAU) scenario to approximately 73 million metric tons per year. For the NYC's harmful gas emission, i.e., PM 2.5, were 55 [tons/sq. miles] in 2005, and the projected emission in 2030 in a BAU scenario is about 68 [tons/sq. miles], about 24% increase. The SD model was calibrated to produce the similar values for energy consumption, and corresponding parameter values of the emission factors were calculated to produce also similar emission values summarized in Table 2. Therefore, the profiles for GHG (i.e., CO_2e) and harmful gas (i.e., PM 2.5) emission for a business-as-usual (BAU) scenario shown in Figure 2 match the emission levels in Table 2.

Table 1: Energy Demand in 2005 and Projected Demand in 2030 for NYC

	2005 (actual)	2030 (projected - BAU)
Electricity Demand [MWh]	50 million	72 million
Heating Fuel Demand [MBTU]	422 million	480 million
Vehicle Combustion Demand [miles]	18.6 billion	24.1 billion

Table 2: Emission of GHG and PM2.5 in 2005 and Projected Level in 2030 for NYC

	2005 (actual)	2030 (projected - BAU)
Total GHG [mt CO_2e]	58.8 million	73 million
GHG from Electricity [mt CO_2e]	23.4 million	34 million
GHG from Heating Fuel [mt CO_2e]	23.6 million	29.2 million
GHG from Vehicle [mt CO_2e]	12.4 million	11.8 million
PM2.5 [tons/ sq. miles]	55	68

As we discussed in the previous section, we modeled and simulated two causal loops. First, we simulated the impact of GHG emission on warmer temperature, which would increase electricity demand for cooling in summer time. We simulated this scenario by introducing arbitrary factors that correlate the warmer temperature to the emission level. Figure 2 includes CO_2e and PM2.5 profiles for 25 year period from 2005 till 2030 for a business-as-usual (BAU) and two different values of the warmer-temperature-factors (WTF1 and WFT2). With a moderate value for the warmer-temperature-factor (denoted as WTF1 hereafter), both GHG and PM2.5 emission increases faster than the BAU scenario. GHG level in 2030 reaches 80 [mt CO_2e] instead of 73 [mt CO_2e] in BAU, and PM2.5 level in 2030 reaches 75 [tons/sq. miles] instead of 68 [tons/sq. miles] in BAU. With a more significant value, the warmer-temperature-factor (denoted as WTF2 hereafter), both GHG and PM2.5 emission increases much faster than the BAU scenario. In this case, GHG level in 2030 is 88 [mt CO_2e] instead of 73 [mt CO_2e] in BAU, and PM2.5 level in 2030 is 83 [tons/sq. miles] instead of 68 [tons/sq. miles] in BAU. This positive causal loop has not been taken into consideration in the NYC report (NYC GHG Emission, 2007) when estimating the emission levels for 2030. The modeling of this causal loop through SD model is potentially useful for a city's policy makers in assessing the emission and developing appropriate emission reduction plans or policies.

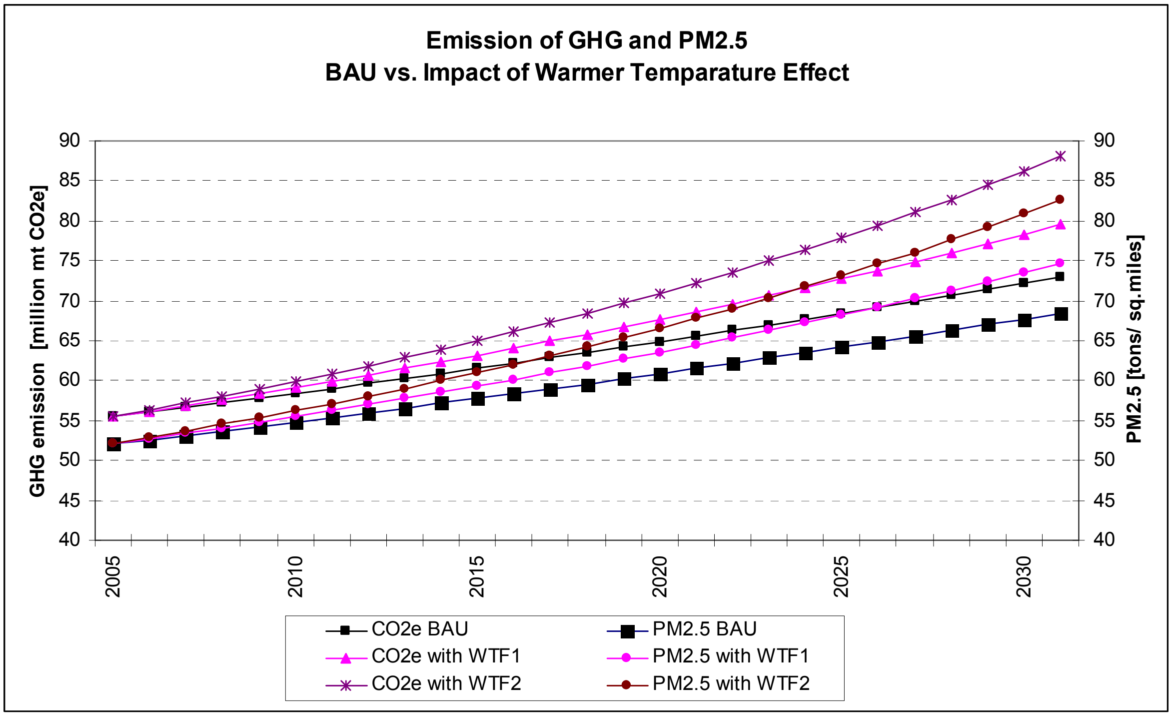

Figure 2: Emission of GHG and PM2.5 for BAU vs. Impact of Warmer Temperature Effect

Secondly, we simulated the impact of investment of energy saving initiatives. The investment not only improves energy consumption efficiency and reduces energy consumption, which leads to emission reduction of GHG and harmful gas, but also creates additional jobs for retro-fitting and retro-commissioning work, which generate more income tax revenue for a city. The higher revenue would allow a city to invest more money for the energy efficiency and energy saving initiatives. The impact of this positive causal loop is simulated in here. We simulated this scenario by introducing arbitrary factors that correlate the levels of energy saving investment to the emission level. Figure 3 shows CO_2e and PM2.5 profiles for 25 year period from 2005 till 2030 for the scenario of a moderate warmer-temperature-factor (WTF1) and two different arbitrary levels of the investment; a moderate investment of $15million/year and a more significant investment of $25mil/year. Note that the exact amount of the investment here are not significant in this simulation study since we are using two arbitrary numbers with different magintude. With $15 million investment, the increases of GHG and PM2.5 emission level didn't change much from 2005 till 2030, i.e., producing 58 [mt CO_2e] and 54 [tons/sq. miles] in 2030, instead of producing 80 [mt CO_2e] and 75 [tons/sq. miles] for GHG and PM2.5 respectively for the scenario for WTF1. With additional investment, i.e., $25 million, the GHG and PM2.5 emission level went down to 43 [mt CO_2e] and 40 [tons/sq. miles] respectively in 2030. This is actually the target for NYC would like to achieve; i.e., reducing the city's emission by 30% below 2005 level by 2030 through the PlaNYC (PlanNYC 2007).

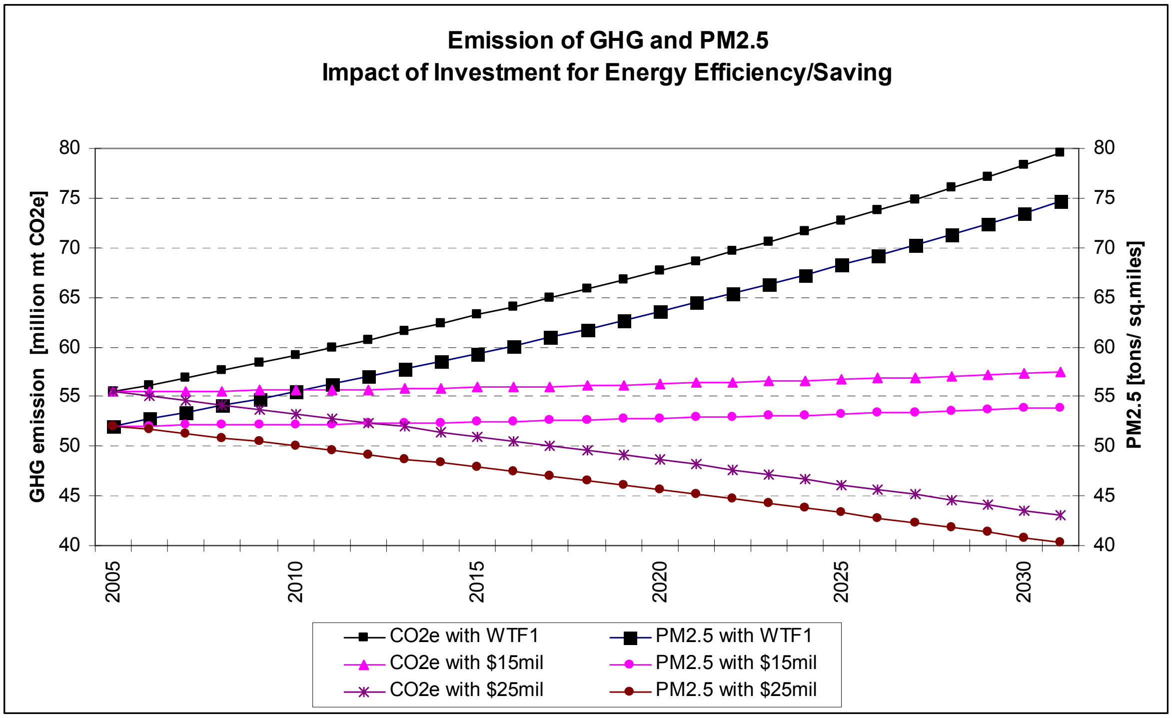

Figure 3: Impact of Investment for Energy Efficiency/Saving on Emission of GHG and PM2.5

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4 Conclusion

Emission of greenhouse gas (GHG) and other harmful gases have significant impact on the various subsystems of a city. Through a system dynamics model, and using data published by New York City, we modeled how consumption of electricity, heating fuel and combustion of vehicle influence the emission levels of greenhouse gases and other harmful gases. Our simulations shows that as GHG emission increases, outdoor temperatures rise, and energy demand increases even faster, which further increases emissions. Our results show that as a city makes investments in energy saving initiatives, the GHG emission level can be drastically reduced and at the same time bring more benefits to the city by generating more income through energy retrofitting jobs, better water management and the improved health of its residents. With what-if capabilities of our model, cities can better understand the causes and impacts of GHG emission, and its dynamic interaction with various subsystems of cities, and develop effective policies for controlling the GHG emission.

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