urban green

U.S. GREEN BUILDING COUNCIL CHAPTER

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90 BY 50: NYC CAN REDUCE ITS CARBON FOOTPRINT 90% BY 2050

URBAN GREEN COUNCIL

Urban Green Council is the New York Chapter of the U.S. Green Building Council (USGBC). Our mission is to advance the sustainability of urban buildings through education, advocacy, and research. Our vision is of cities that coexist in harmony with their natural environment and contribute to the health and well-being of all.

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DISCLAIMER

UPDATE
11 September 2013: Errors in Tables 2.1, 4.2, 5.1, 5.2, 7.1, and 8.1 are corrected in this version.

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ABSTRACT

New York City has undertaken many cutting-edge energy efficiency and greenhouse gas reduction programs. The Greenhouse Gas Inventory project, the Greener, Greater Building Plan, building code improvements derived from the Green Codes Task Force, and Zone Green from the Department of City Planning have all served the city's plaNYC goal of reducing the city's greenhouse gas emissions 30 percent by 2030.

This has been a noble and largely successful effort to date. But it is not enough. To ensure a global environment in which human society can bring security and prosperity to all its members, climate science tells us we must reduce carbon pollution dramatically. A figure of 80 percent globally by 2050 is often cited. A reduction of 90 percent in the readily measured fraction of the city's emissions will be necessary to meet this goal, and this study outlines an energy economy for New York City in 2050 that will match this challenge.

This study focuses primarily on the building sector, the source of 75 percent of New York City's greenhouse gas emissions. Building simulation modeling using eight basic building types shows that heating and cooling loads can be dramatically reduced through air sealing, heat recovery ventilation, and additional insulation, to a point where all heating, cooling, and hot water can be provided by electric heat pumps. Analysis of the city's building stock shows that the total electric load in 2050, which must be supplied by carbon-free sources, will be slightly more than today's electric load. Over the period examined, and on the basis of today's prices for both fuel and improvements, the lifetime savings from energy use reductions will be comparable to the costs of the building improvements.

In the transportation sector, electrification and expansion of both passenger and freight rail and conversion of on-road vehicles to electric drive, hybrids, and turbo diesels, coupled with the recently enacted federal fuel economy standards, will allow total residual carbon emissions to drop well below 10 percent of today's levels.

After reducing total building energy use by 50 to 60 percent, all building energy must be supplied by carbon-free electricity, up from 39 percent in 2010, in order to meet our 90 percent reduction target. Potential sources of adequate carbon-free electricity are enumerated, but detailed analysis is beyond the scope of this study. Contributions from rooftop photovoltaic panels will be significant. Electricity generation from biogas derived from waste and sewage treatment provides an additional input of carbon-free power while consuming a potent greenhouse gas.

Several other alternatives, such as maintaining the district steam system on waste combustion, are discussed but were not incorporated in the analysis.

Although not a blueprint or detailed plan for the next 37 years, 90 by 50 demonstrates that the extreme emission reductions required to minimize climate change are in fact possible using technologies that are known and in almost all cases currently available, and that the costs are comparable to the lifetime savings.

1. SUMMARY

Figure 1.1: View of Manhattan from Brooklyn

INTRODUCTION

Nearly all climate scientists[1,2] tell us that to avoid catastrophic global warming we must dramatically reduce carbon emissions in the global economy by 2050. The devastation caused by hurricane Sandy has re-focused attention on both adapting to the threat posed by climate change and the necessity of acting to mitigate that threat.

For developed countries, emissions must be at least 80 percent below current (2010) levels by 2050 to permit convergence on a CO_2 concentration likely to be less than 450 parts per million, which would in turn probably result in global temperature increases of less than 2°C (3.6°F). For New York City, a more challenging goal, a reduction of more than 80 percent, is appropriate for several reasons:

- The city's greenhouse gas (GHG) accounting does not incude several important categories of emissions.
- New York City's mass transportation system can attract even more passengers to carbon-free modes of travel.
- A 90 percent target leaves a little more "breathing room" if some reduction measures turn out to be impractical.

As a result, we have chosen a goal of reducing New York City's greenhouse gas emissions by 90 percent by 2050. The year 2050 is 37 years away, and many political and economic shifts are possible during that period. Consequently, in determining the feasibility of this goal, we have focused on what is physically possible with presently available and reasonably foreseeable technology. We did not restrict our analysis by current political constraints, and gave only moderate attention to economic constraints.

A 90 percent cut in emissions correlates with a smaller reduction in energy use, since the path we examined included carbon-free electricity. After maximum building energy reductions were made, the remaining loads were supplied with this electricity rather than fossil fuels. Energy from rooftop photovoltaic panels was included. For the remaining supply, we computed the required electrical energy and demand, and listed options that could supply the carbon-free electricity needed to augment the 39 percent already in the New York City mix.

We refer to “measures” rather than “proposals” to recognize that we are not recommending any particular steps, but are rather constructing one model scenario to show what is possible. Practical scenarios may differ dramatically in approach and in which specific reduction measures are actually implemented.

With the resources available, a detailed sector-by-sector study examining intermediate trajectories over the coming decades was not feasible. Instead, we examine the city as a whole, and look only at the two endpoints, 2010 and 2050. We believe this allows us to sketch a credible future that meets the “90 by 50” goal. It must, however, be seen as an initial effort, in need of significant refinement and expansion, before it can serve as a basis for specific policy proposals.

WHERE NEW YORK CITY IS NOW

This study was restricted to sources and sectors included in the plaNYC report, “Inventory of New York City Greenhouse Gas Emissions” (*Inventory*). Because buildings are responsible for most of the city’s GHG emissions, they were the focus of our study, but emissions from several other sources are included as well.

The study started with a model of NYC buildings with which we reproduced current NYC GHG emissions within the building sector. We modeled the building sector using eight different building types representative of the building stock of the city, and used a widely accepted building simulation model (DOE-2) for each building type to estimate its particular current GHG emissions. Each model describes a well-defined building, the characteristics of which were selected to represent those of that building type across the entire city, as taken from the city’s tax lot and building database. Internal electric and fuel loads were apportioned using data from a recent Con Edison study of citywide energy use, the city’s benchmarking results, DOE-2 internal assumptions, and other standard sources.

The eight building types represented by our models are:

- One or two family detached house
- Three story row house
- Low rise apartment building
- Two high rise residential towers:
  - Masonry with punch windows
  - Window wall
- Low rise commercial building
- Two high rise commercial towers:
  - Masonry with punch windows
  - Curtain wall

We scaled these results up to assign emissions citywide stemming from each building type, using the ratio of the citywide floor area corresponding to that building type to the floor area in that model. Building types may be served by more than one fuel, so we allocated each building model across fuel types as part of the scaling process. After these parameters were applied, we also made various adjustments to building characteristics, so that in the end the building emissions scaled up from the 2010 models matched those from the *Inventory*, correctly allocating the emissions among building types. Building characteristics were also adjusted so that usage would match known fuel and electricity use data from the *Inventory*, the Con Edison study, New York City’s benchmarking data, and other sources.

WHERE WE MUST GO – REDUCTIONS IN BUILDING EMISSIONS

We used a two-step process to determine the 2050 GHG emissions reductions in buildings. First, we used available projections of population and employment to estimate total future building area corresponding to each of our eight models. Second, we applied a wide variety of energy efficiency technologies to both currently existing and newly constructed buildings to minimize their energy use and to provide for all-electric provision of remaining services. We did not distinguish

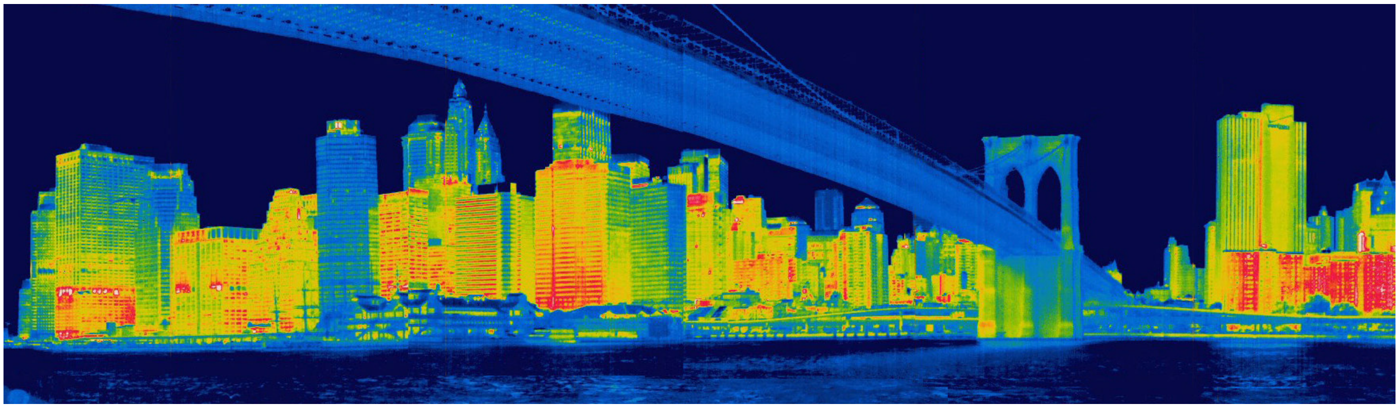

Figure 1.2: Infrared image showing heat loss from New York City buildings

between new construction and retrofits when developing projections for 2050. Consequently, the process of scaling up the 2050 loads and emissions from the building models to citywide values was the same as for the 2010 buildings.

The major building energy efficiency technologies employed were:

- Substantial air sealing and heat recovery systems for ventilation air;
- High levels of insulation on all opaque elements of building facades;
- Vision glass fractions limited to 50 percent (while retaining useful daylighting) and triple glazing on all vision glass;
- Sun control devices permit winter solar heat gain while minimizing summer cooling loads;
- Photovoltaic panels to produce renewable electricity on site; and
- Mini-split heat pumps for most apartments, and ground-source heat pumps for commercial and larger residential buildings. Air-source heat pumps provide hot water.

In addition, various foreseeable technologies will lower currently substantial in-building loads, and were employed in our models. In residences and commercial buildings, heat pump clothes dryers, induction stoves, and air source heat pumps for hot water will lower energy use dramatically. With proper design, most server farms can be cooled with near-ambient air. We found that many of the measures introduced to mitigate climate change also increase building resilience, providing adaptation to that climate change. For example, greater thermal integrity ensures buildings that will remain more habitable without services such as heat, hot water, or electricity.

The age of the Con Edison steam system has made ongoing operation challenging, but district heating also has many advantages. A brief scoping analysis indicated that in-city biomass sources, if targeted toward running the steam system, would provide sufficient energy to replace the fossil fuels currently used, were this approach found operationally feasible. We did not, however, rely on this approach in our final energy use estimates, but assumed that all buildings will undergo the shift to all-electric operation.

WHERE WE MUST GO – REDUCTIONS IN OTHER EMISSIONS

The other significant source of emissions in New York City is transportation. We developed a model of the various transportation modes in New York City based on passenger- and ton-miles traveled. We used the model to project the emissions that will result after as much traffic as possible is switched to electrified modes and improved efficiencies have been realized in each mode. Some of the assumptions were:

- The recently implemented federal mileage standard of a fleet average of 54.5 miles per gallon will be fully implemented by 2050;
- Many bus routes will be converted to electric trolleys;
- Substantial shifts to hybrid vehicles will occur;
- The MTA's current plans to use weight reduction and regenerative braking result in substantial savings in traction energy; and
- Improved rail access, including the Second Avenue subway, the Hudson River passenger tunnel, and the under harbor freight tunnel will decrease dependence on cars, buses, and long-haul trucking.

In another area, fugitive methane emissions from wastewater comprise 2 percent of city GHGs. If capture technologies can be broadly extended, these emissions can be almost completely avoided by use of the gases for electric generation, and similar reductions in fugitive gases from solid waste landfills are possible. We extrapolated from current efforts to estimate very low fugitive emissions in 2050.

CONCLUSIONS

Our modeling indicates that by 2050 New York City could reduce its greenhouse gas emissions more than 90 percent from 2010 levels through a combination of existing and near-term efficiency technologies and shifting all remaining building loads to carbon-free electricity. In our analysis, buildings will remain functionally the same as today, without sacrificing physical comfort. (Indeed, we assumed substantially more widespread air conditioning.)

Taking into account natural replacement cycles, our team developed cost estimates for improving each of our eight buildings. Spread over 35 years from 2015 to 2050, the corresponding capital outlays for the entire city have a discounted net present value of $94 billion. We also developed a rough estimate of the financial savings that would accrue from the building energy use reductions, which had a net present value of $87 billion. Although the challenges involved in promoting investment in these improvements are substantial, the entire project is cost neutral when aggregated over the economy of the entire city and other factors, described within, are included. We did not develop cost or savings estimates for improvements to the transportation and waste sectors.

The results for our analysis of deep building retrofits are shown in Table 1.1. The amount of carbon-free electric power that must be provided to operate the entire city under our models is comparable to 2010 total consumption, although peak demand is larger. We developed a list of carbon-free technologies that could supply the needed electric energy, but did not analyze the details of this shift from 39% carbon-free electricity in 2010 to 100% in 2050.

For the building sector, we established a set of target energy-use intensity (EUI)† figures that, if met, will allow the city to meet the 90 percent reduction target. A different target EUI was derived for each of our eight building types, and are shown in Figure 4.8. EUIs for our 2050 buildings if they were supplied with the 2010 electric supply mix indicate reductions of 50 to 60 percent from 2010 values and show that our targets are significantly less demanding than the Passive House standard. When the 2050 buildings are supplied with carbon-free electricity, the EUIs range from 16,000 Btu per square foot for the high-rise residential masonry building to 43,800 Btu/sf for the low rise commercial building, very low by today's standards, but an indication of what a sustainable future will look like.

† EUI is the energy used in a bulding in one year, divided by the floor area of the building.

Table 1.1: Summary of Changes in Emissions and Fuel Use				
Year	Gross Electric Generation Required (Million kWh)	Gross Electric Generation Required (Trillion Joules)	Non-Electric Source Energy (Trillion Joules)	CO_2e Emissions (Million Metric Tons)
2010	52,500	189,000	598,000	54.3
2050	57,000	205,200	42,300	3.2

NEXT STEPS

Other paths to deep emission reductions are certainly possible, and several different approaches should be studied, but knowing that at least one approach can work should provide impetus for both action and further investigation. Several areas for future work are already clear:

- We must determine whether the very deep cuts in building energy use that we have examined are optimal, or whether lesser cuts combined with greater deployment of carbon-free electricity would be less expensive.
- How large a workforce is needed to implement a program on this scale and will it be possible to train this workforce in the available time? (Some very early estimates follow.)
- Are there material constraints on supplies or equipment that would make the required renovation and construction difficult or impossible?
- Can the work proceed incrementally for some buildings, or is a total rehab the optimal way to proceed?
- How might the work be financed?

And, of course, many issues will arise when the political and economic aspects of such a project are investigated in greater depth, issues that we have purposely avoided, but that must be addressed in the near future.

90 BY 50 - BUILDING TECHNOLOGIES

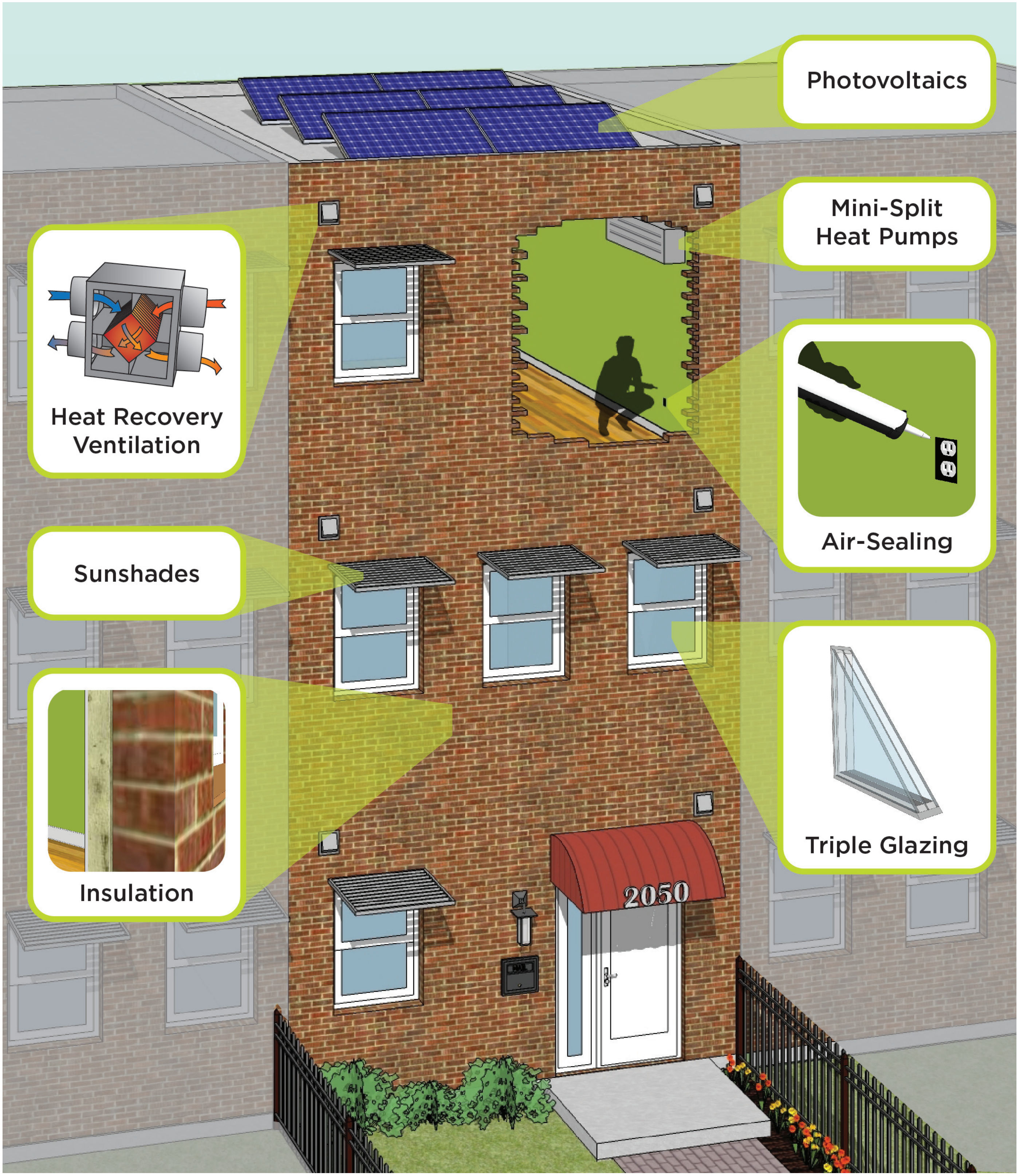

Figure 1.3: A sample of the energy efficiency measures used in the 2050 building models.

90 BY 50 - LET'S GET TO WORK!

The New York City Building Congress estimated a total of 112,400 construction jobs in NYC in 2010. "90 by 50" would create the demand for at least 11,060 construction jobs per year, increasing employment by almost 10 percent from 2010 levels[3,4].

Figure 1.4: 6,500 construction workers[†] will be needed each year from 2015 to 2050 to install a total of 5.7 billion square feet of insulation to building roofs and walls.

Figure 1.5: 86,000 commercial buildings and 5.65 million residential apartments will be fitted with heat or energy recovery systems.

Figure 1.6: The installation of 99 million windows, 45 millions square feet of window wall, and 31 million square feet of curtain wall will create 2,700 construction jobs each year from 2015 to 2050.

Figure 1.7: 5.65 million residential apartments and 2.12 billion square feet of commercial floor area will require air sealing, creating 1,860 new jobs each year from 2015 to 2050.

2. OUR BASELINE: 2010

To learn how we can reduce New York City's carbon footprint, we must first understand clearly what that footprint is at our starting point: calendar year 2010.

NEW YORK CITY EMISSIONS

Greenhouse Gas Emissions Inventory

Since 2007, New York City has maintained a detailed accounting of greenhouse gas (GHG) emissions as part of plaNYC[1]. The most recent of these reports, "Inventory of New York City Greenhouse Gas Emissions – September 2011"[2] (*Inventory*) provides a deep picture of emissions in calendar 2010, which we used as our base year.

The *Inventory* provides fuel use and GHG emissions data in broad categories and numerous subcategories. Our report is structured around the following broad categories, in order of importance:

- Buildings
- Transportation
- Fugitive and Process Emissions
- Streetlights and Traffic Signals

The detailed subcategories vary and will be explained as needed. The bulk of the work in our report is focused on the buildings sector, which produced 75 percent of New York City's GHG emissions in 2010.

CO_2 Equivalents for Other Greenhouse Gases

Carbon dioxide (CO_2) is not the only GHG contributing to climate change. Others include natural gas (primarily methane, CH_4), nitrous oxide (N_2O), vapors used in air conditioning equipment, and various other industrial and natural chemicals. A complete list is maintained by the IPCC[3]. Each of these gases has a known global warming potential, which can be measured relative to that of CO_2. To avoid listing emissions of large numbers of different gases, the *Inventory* and most similar studies present total emissions in terms of CO_2e (for equivalent), the amount of pure CO_2 that would match the overall global warming effect of the total group of gases. This is normally written as: "In 2010, New York City emitted 54 million metric tons of CO_2e, which corresponds to about 6.5 metric tons per New Yorker." (The United States as a whole emits about 19 metric tons CO_2e per citizen per year.) We will present emissions of individual gases where appropriate, but all total emissions will be described using CO_2e.

Emission Sources: Scopes 1, 2, and 3

Where possible, the *Inventory* complies with a standard developed by the California Air Resources Board, the Local Government Operations Protocol (LGOP)[4], which is widely used by local governments reporting GHG emissions. The LGOP divides emissions into three categories:

- Scope 1: Direct emissions, such as from boilers and cars
- Scope 2: Emissions due to energy consumed in the city but generated elsewhere, such as electricity
- Scope 3: Emissions from activities connected to the city, but that occur elsewhere, such as aviation fuel delivered to city airports or production of food consumed in the city

Following the example of most local governments, the *Inventory* does not include Scope 3 data in the nominal total New York City emissions, although it does present available data. (The *Inventory* total for Scopes 1 and 2 is 54 million metric tons, while Scope 3 adds another 14 million metric tons, almost all of it airplane fuel.) While airline emissions must be reduced, the city has very little control over Scope 3 items, and it is an area where we lack expertise and data. Our report will follow the city's protocol, and will not study Scope 3 emissions in either 2010 or 2050.

The rest of this section develops the assumptions used to create a model of the building sector and calibrate it to the data in the *Inventory*. Some of the details are presented in Appendix A. For the transportation and fugitive and process emissions sectors, the 2010 calibration and subsequent reduction strategies are developed in the sections devoted to those sectors.

BUILDING SECTOR

Approach

Our goal was to describe all the buildings in New York City in a way that allows us to calculate total current and future emissions of greenhouse gases. To do this, we first selected eight types of buildings that spanned the structures of the city. We then defined the characteristics of these building types, using data from the NYC Dept. of Finance's PLUTO database[5] on existing city buildings, to determine how many actual buildings correspond to each of our eight building types, and what total citywide floor area each type occupies. This data allowed us to scale the emissions of individual buildings up to citywide levels for comparison with *Inventory* values. In an iterative process, described in more detail on the following pages, we also

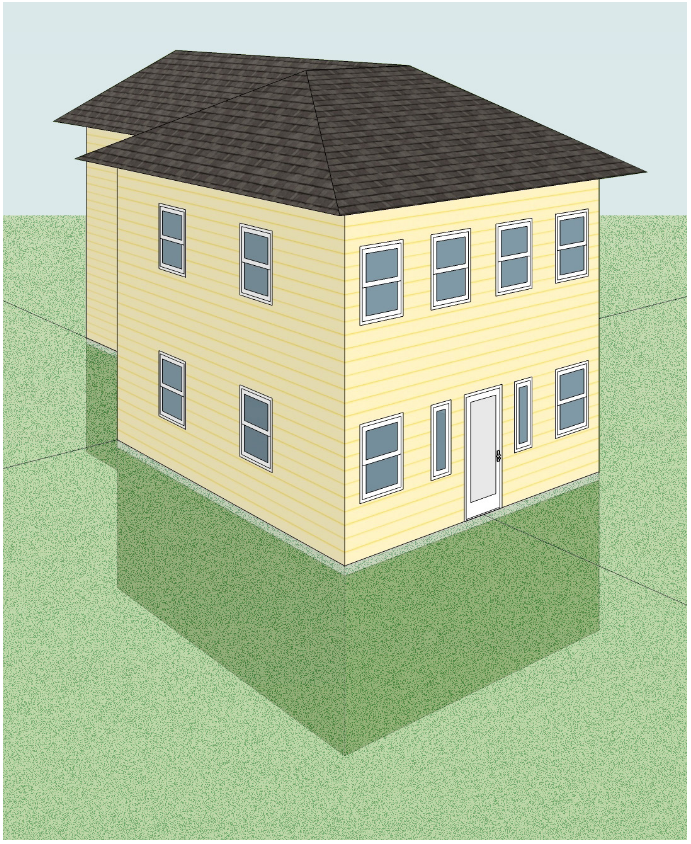

Figure 2.1: One or Two Family House, 2010
(Basement shown as dark shadow.)

determined the dimensions for each building that would make them most representative of that building type.

We then prepared detailed models of each of these buildings using the eQUEST building energy simulation program[6], and adjusted the building characteristics so that each building's energy use corresponded to current energy use estimates, and the total citywide fuel use and CO_2 emissions from buildings agreed with the *Inventory*.

Building Types

The *Inventory* provides data on four categories of buildings in New York City: residential, commercial, industrial, and institutional. Given our resources and limitations on available data, we subsumed all nonresidential buildings into one category, which we refer to as "commercial," although it includes schools, churches, and garages. Table 2.1 presents the basic characteristics of our eight building models. The derivation of these characteristics is presented in the following sections.

Building Characteristics and Populations

Several steps were needed to ensure that each of our models represented a significant amount of floor space in New York City, but that none of that space was represented by more than one model. Specific ranges of data such as building area, dimensions, and number of floors were assigned to each building type, such that all buildings in PLUTO could be allocated between the eight prototype models. Each record in PLUTO corresponds to a single tax lot, which often contains more than one building. In that case, the total floor area gives

Table 2.1: Physical Characteristics of Building Models

Building Type	Stories Above Ground	Area (sf) Above Ground	Dwelling Units	Construction Type	Footprint
1 or 2 Family House	2	1,352	1 or 2	Wood Frame	"L" Shaped
Row House	3	1,992	2	Masonry	Rectangular
Low Rise Residential	4	8,558	9	Masonry	"U" Shaped
Masonry High Rise Residential	15	123,000	117	Masonry: Punch Windows	"U" Shaped
Window Wall High Rise Residential	26	184,800	142	Floor to Ceiling Glazing	"U" Shaped
Low Rise Commercial	2	15,170	N/A	Masonry	Rectangular
Masonry High Rise Commercial	17	229,200	N/A	Masonry: Punch Windows	Rectangular
Curtain Wall High Rise Commercial	21	192,800	N/A	Steel Frame / Curtain Wall	Rectangular

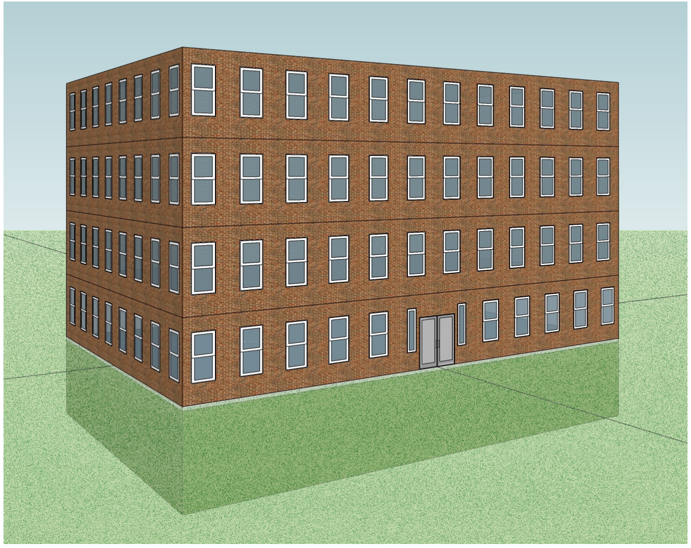

Figure 2.2: Low Rise Residential Building, 2010

the correct number for the lot, but other characteristics, such as height and footprint, describe the "principal building" on the lot. We used these PLUTO data fields to determine the building type representing the entire lot. This allowed us to assign each lot to one of the eight building types and derive total citywide floor areas corresponding to each type. Some of our criteria follow:

- **Floor Area for Residential and Commercial Sectors:** Total floor area in each lot was strongly skewed toward either residential or commercial use in most cases. A lot was deemed residential if 50 percent or more of the total building floor area was listed as residential, commercial if less than 50 percent.
- **Low Rise and High Rise Buildings:** PLUTO data revealed that almost all floor area was concentrated in buildings with either substantially more than seven floors or substantially less than seven floors. We accordingly used seven floors as the cut-off value between low rise and high rise buildings.
- **Proximity Code:** The PLUTO data field "Proximity Code" specifies whether a building is detached, semi-attached, or attached. Smaller residential buildings were classified as row houses if attached or semi-attached, and as 1-2 family houses or residential low rise (based on size) if detached.
- **Masonry and Window Wall, Masonry and Curtain Wall:** PLUTO contains no information regarding building construction materials, and no other citywide information was readily available. To distinguish construction types, we used the data field, "year built" as a proxy. For the residential sector, the more modern window wall architecture was assigned to buildings constructed in 2000 or later, as long as they had 12 or more floors. All other residential high rise buildings are considered masonry. For commercial buildings, all buildings constructed before 2000 were designated as masonry, while high rise buildings constructed during or after 2000 were designated as curtain wall. The selection of 2000 as a cut-off year was based on discussions with members of the construction community, but is clearly somewhat arbitrary.

These and other criteria are summarized in Table 2.2, and the resulting citywide areas corresponding to each building type are shown in Table 2.2 and Figure 2.3.

With these assignments complete, the eight building models were refined by evaluating the average values of the number of floors and, for residential buildings, dwelling units from PLUTO data for each building type. The floor area per building in each category was found by considering all the buildings in that

Table 2.2: Criteria for Classification of 2010 Citywide Building Area

Building Type	Stories Above Ground	Area (sf) Above Ground	Time Period	Number of Buildings	Citywide Area (Million sf)
1 or 2 Family House	1 to 3	< 3,001	All	340,273	460
Row House	1 to 4	< 5,001	All	389,887	777
Low Rise Residential	1 to 7	(Excluding 1-2 Family and Row House)	All	170,714	1,461
Masonry High Rise Residential	8 to 150	N/A	1700 - 1999	6,363	782
	8 to 12	N/A	2000 - 2010		
Window Wall High Rise Residential	13 to 150	N/A	2000 - 2010	388	72
Low Rise Commercial	1 to 7	N/A	All	69,352	1,052
Masonry High Rise Commercial	8 to 150	N/A	1700 - 1999	2,941	674
Curtain Wall High Rise Commercial	8 to 150	N/A	2000 - 2010	271	52

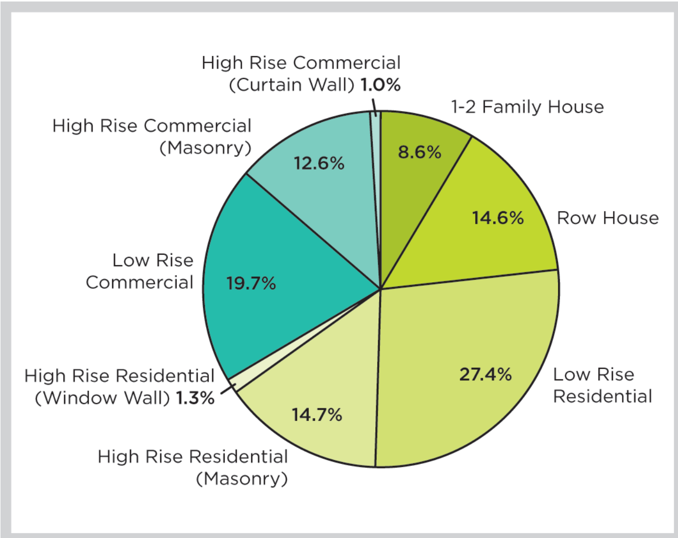

Figure 2.3: Citywide Building Area Breakdown by Building Type

category and dividing the total floor area by the number of buildings. These data are shown in Table 2.1.

The shape of the buildings varied to match the data. For the row house and all commercial buildings, we adjusted the frontage and depth to give a rectangular footprint and floor area that agreed with these overall average floor areas. For the one or two family house, we adopted an L-shaped footprint, and for the other residential buildings, a U-shaped footprint, with dimensions chosen so that the frontage and depth agreed with the average values of the principal buildings for each type, while the areas agreed with the overall averages for that type. Sample footprints are shown in Figure 2.4. In this way, the building models fully represent the varied range of building types that are present citywide.

Building Simulation

Detailed building simulation models of each of the eight building types form the core of this study. This section, supplemented by Appendix A, presents details of these models and describes how their outputs are scaled up to permit calibration against known current fuel use and carbon emissions.

eQUEST/DOE-2.2 Models

DOE 2.2 is a widely used and comprehensive building simulation model. Able to represent many construction types, equipment choices, and building characteristics such as air infiltration and solar gain, it calculates thermal energy gained or lost, and the equipment operations necessary to maintain specified indoor conditions hourly for periods of up to one year. eQUEST is a user-friendly graphical interface to DOE 2.2 that makes definition of a building model much easier than it would be if working directly with DOE 2.2.

The construction techniques modeled in each building type were typical for such buildings, but were adjusted to calibrate energy use to citywide totals. Some of our initial models were based on simulation files graciously supplied by the Department of City Planning, which they regarded as more or less representative of city building stock. (We have so modified the models since then that the department is in no way responsible for any aspect of our results.) Several key parameters for each building are shown in Table 2.3. All buildings were assumed to have double-glazed windows or curtain walls, and to use gas for cooking and laundry dryers.

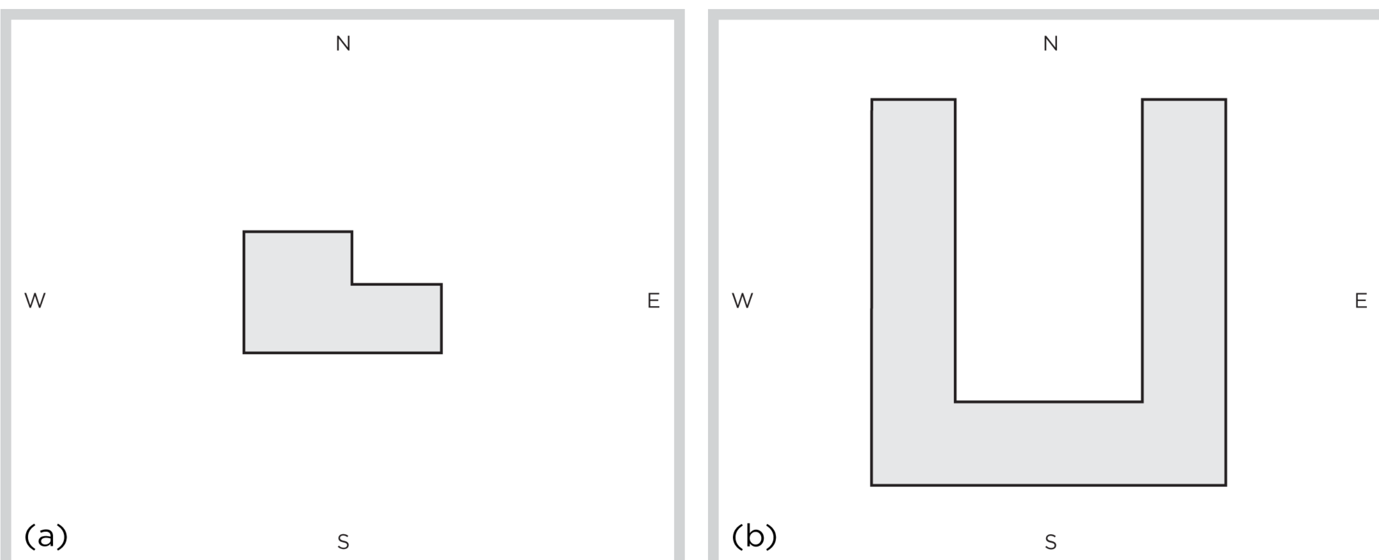

Figure 2.4: Sample footprints for (a) L-shaped building and (b) U-shaped building.

Building Energy Use

Every building consumes energy for heat, hot water, building services like elevators and pumps, appliances, cooking, and a host of other end uses. To provide accurate models with which to assess our ability to reduce these loads, we had to insure that simulate energy consumption agreed with a variety of data sources, including:

- The Inventory (both fuel use and emissions),
- New York City Benchmarking results,
- Internal eQUEST default values for some quantities such as pumping energy, and
- Other detailed studies of energy use in buildings, either in New York City or of national scope.

The overall goal was to develop eight model buildings that, when looked at as individual buildings, could reasonably present the operating characteristics of actual buildings of that type, and which, when energy use was scaled up using the ratio of all the floor area in the city of that type to the floor area of that building, would reproduce the fuel use and emissions reported in the *Inventory*. The process for carrying this out was complex, and is reported in detail in Appendix A. Here we touch on a few key points.

First, each building type may have its heat and hot water needs served by more than one fuel, including gas, oil (#2, #4, and #6), electricity and Con Ed steam, as shown in Table 2.3. Rather than create separate eQUEST models for each heating system, we created one model of each building and used it to find the actual heating and hot water loads. Then we calculated fuel use for each type of heat used in each building,

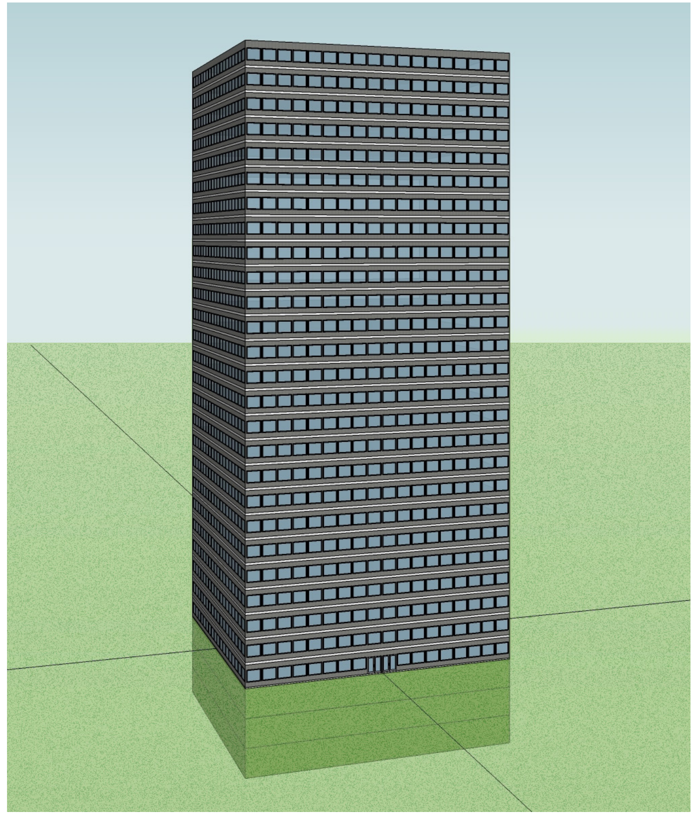

Figure 2.5: High Rise Window Wall Residential Building, 2010

Table 2.3: Energy Characteristics of 2010 Building Models

Building Type	Glazed Fraction	Air Conditioning Type	Plug Loads (W/ft^2)	Ambient Lighting	Main Fuel Types	Source EUIs (kBtu/sf)**
1 or 2 Family House	15%	Window	0.7	Mostly Incandescent	#2 Oil, Gas, Electric*	153
Row House	30%	Window	0.6	Mostly Incandescent	#2 Oil, Gas, Electric*	144
Low Rise Residential	30%	Window	0.6	Mostly Incandescent	Gas, #2 Oil, #6 Oil, #4 Oil, Electric*	136
Masonry High Rise Residential	30%	Window	0.7	Mostly Incandescent	Gas, #6 Oil, Steam, #4 Oil, #2 Oil, Electric*	113
Window Wall High Rise Residential	50%	PTAC	0.7	Mostly Incandescent	Electric, Gas	136
Low Rise Commercial	30%	Rooftop	1.0	Fluorescent	Gas, #2 Oil, Steam, Electric*, #4 Oil, #6 Oil	290
Masonry High Rise Commercial	30%	Central	1.3	Fluorescent	Gas, #6 Oil, Steam, #2 Oil, #4 Oil, Electric*	217
Curtain Wall High Rise Commercial	60%	Central	1.3	Fluorescent	Gas	222

* Electricity is used for less than 3% of buildings
** Source EUIs computed at 9,547 Btu/kWh (See text and Appendix A)

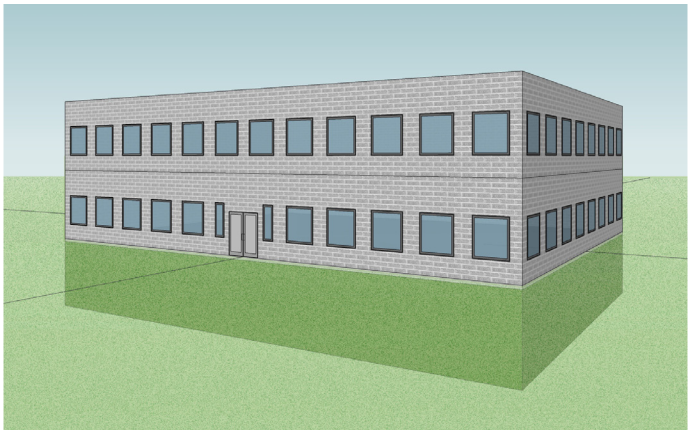

Figure 2.6: Commercial Low Rise Building, 2010

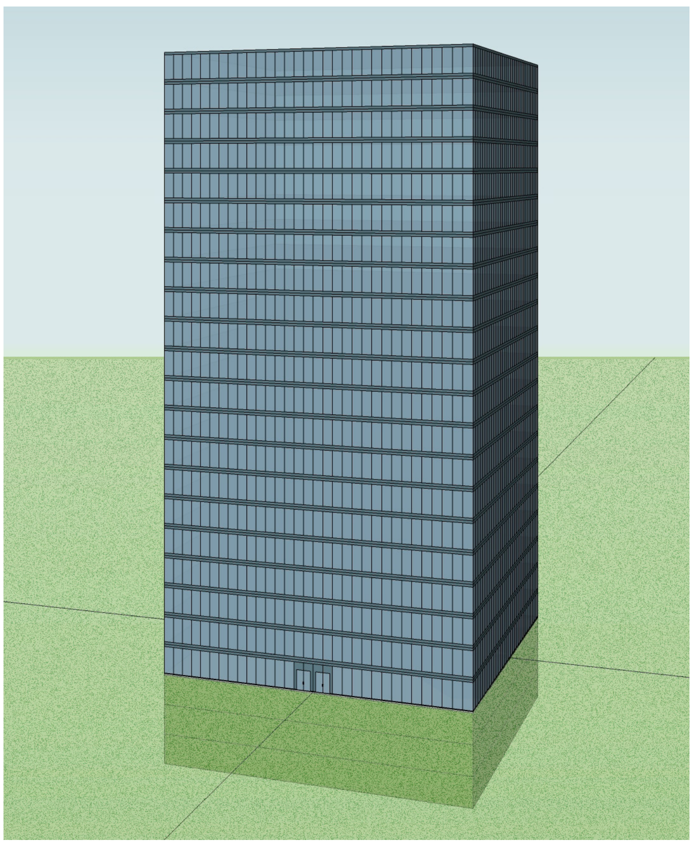

Figure 2.7: Curtain Wall Commercial High Rise, 2010

incorporating standard assumptions on the efficiency of each system. Matching building fuel use and emissions to those in the *Inventory* was achieved by making adjustments to building characteristics such as infiltration, insulation, and the efficiency of the fuel-using equipment.

Table 2.3 includes a column indicating the source EUI we found for each building model. The source EUI of a building includes both the energy consumed within the building (known as "site EUI") and the energy used to produce that energy. The fuel used in power stations to generate electric energy is roughly triple the energy delivered as electricity. As is explained in more detail in Appendix A, the appropriate ratio for New York City in 2010 was 2.867, a heat rate of 9,782 Btu/kWh, and we used this rate in calculating source EUIs in 2010 for Table 2.3.

Emission Summation

The fuel and electricity use for each building model was then scaled up to represent usage of each fuel and electricity from all the buildings in that type, using the ratio of all the floor area in the city corresponding to that type of building to the floor area in that building model. The associated emissions of GHGs were also calculated using the conversion factors from the *Inventory*, and compared to *Inventory* emissions in the buildings category.

The *Inventory* lists fuel use and emissions separately for #2, #4, and #6 fuel oil and for electricity, steam, and natural gas. Matching our citywide totals to the *Inventory* totals provided the constraints that allowed us to determine the fuel splits in each building type, although there was some leeway in exactly how the splits were assigned.

The result of this exercise was a full-scale model of building energy consumption and emissions in New York City, based on eight building types, detailed data on the characteristics of buildings, and sophisticated models of the energy performance of the eight building types. Calculated fuel use and emissions for the entire city agreed with those in the *Inventory* to one percent or less. As described in succeeding sections, this model was then used to show how energy use in the building sector can be drastically reduced.

3. WHERE WE MUST GO: REDUCTION TARGETS

GLOBAL AND NATIONAL REDUCTION TARGETS

According to a broad consensus of climate scientists, the world must reduce greenhouse gas (GHG) emissions by 80 percent by 2050 to be confident that atmospheric concentrations of CO_2 can be held below 450 parts per million (ppm)[1]. (It was historically 280 ppm, and has now risen to 390 ppm.) This will make possible a global temperature increase of less than 2°C, providing some level of assurance that dangerous climate change can be averted. A detailed analysis shows that if these requirements are to be met in the long term, industrialized countries must also reduce their emissions by 80 percent below 2000 levels by 2050[2], and we use this goal as a starting point.

NEW YORK CITY'S TARGETS

Unfortunately, accurate GHG emissions data for the city date back only to the first year of the *Inventory*, 2005. Emissions actually declined 12 percent from 2005 to 2010, due largely to improved utility operations. However, in all likelihood they increased along with those of the rest of the U.S. from 2000 to 2005. Given good data for 2010, and the likelihood that the 2010 levels are not too far from 2000 levels, we have elected to use 2010 as our base year.

If a goal of an 80 percent reduction in emissions by 2050 is appropriate for the U.S. as a whole, it is too modest a goal for New York City for several reasons.

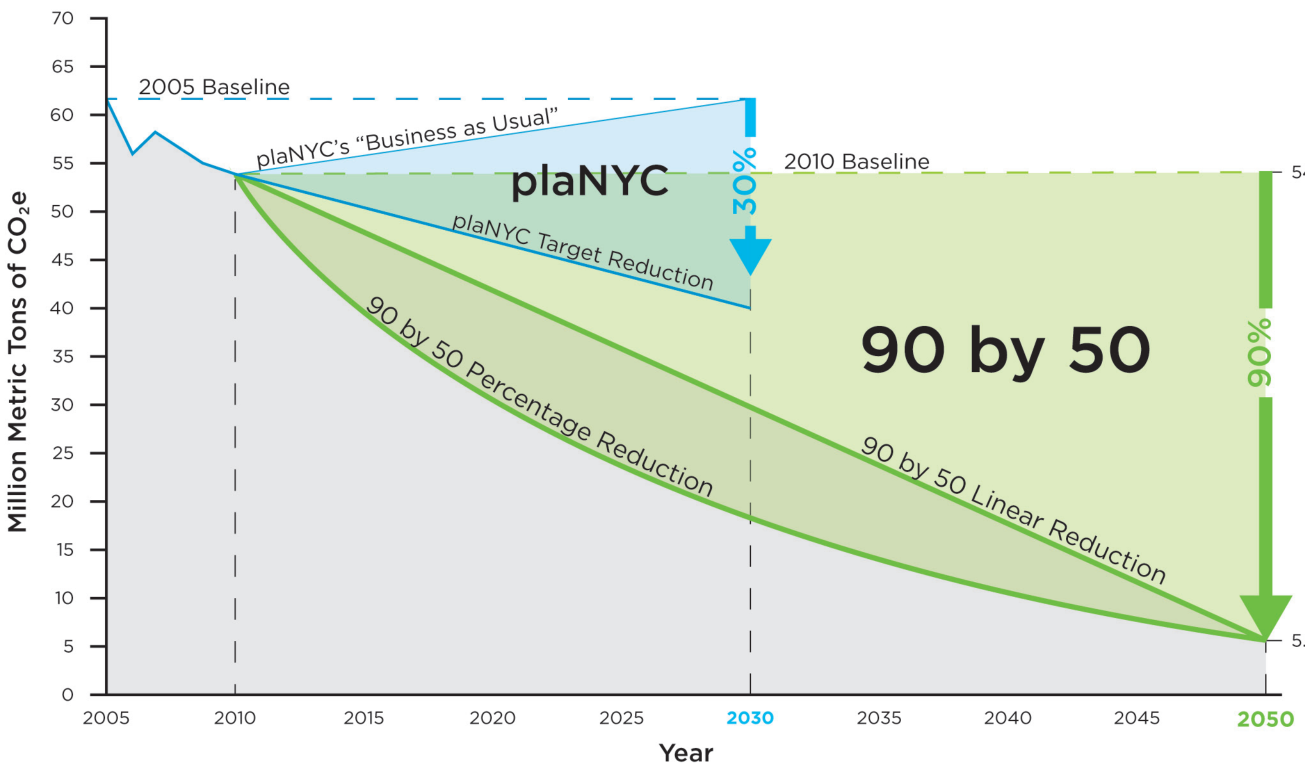

Figure 3.1: 90 by 50 trajectories compared to plaNYC goals.

- First, our analysis is based only on Scope 1 and Scope 2 emissions. This means that none of the emissions associated with feeding and clothing our population, building our homes, offices, and roads, and flying to other cities or countries are included. It is not at all clear what an appropriate adjustment would be, but aiming for an additional 10 percent reduction is a step in the right direction.
- Second, some of our reduction measures will fail or prove more difficult or expensive than is now thought, and some margin for slippage is important, given the seriousness of the threat and the uncertainty of the analysis.
- Finally, New York City, with its dense urban environment and efficient transportation, already has very low per capita emissions, but may still be in a position to do more than other, more dispersed regions of the country, which are more dependent on motor transportation. Because we *can* lead, we *should* lead.

So, although there is clearly much room for discussion, our target is a 90 percent reduction, rather than 80 percent.

For comparison, Figure 3.1 shows the emissions goals of this report superimposed on plaNYC's goal of a 30 percent reduction by 2030[3]. The figure shows two ways to approach the "90 by 50" goal: one of constant percentage reductions, lowering emissions by 5.6 percent each year, and one of constant reductions of 1.2 million metric tons per year. The percentage reduction trajectory will result in 880 million metric tons total emissions over the 40 years of the effort, far less than the 1,225 million metric tons that would be emitted if the constant reduction trajectory were to be followed. The figure also shows that in either case, the current plaNYC goals are not stringent enough to put us on a path to a 90 percent reduction by 2050.

Figure 3.2: Dumont Green in Brooklyn is partially powered by 80.5 kW of electricity from its photovoltaic system.

Table 3.1: 2010 Emissions and 2050 Targets

Sector	2010 (Million Metric Tons CO_2e)	2050 (Million Metric Tons CO_2e)	Reduction
Buildings	40.6	0.0	100%
Transportation	11.4	5.2	54%
Fugitive and Process	2.28	0.26	88%
Streetlights and Signals	0.08	0.0	100%
Total	**54.3**	**5.4**	**90%**

APPROACHES TO EMISSION REDUCTIONS

Next, we determined what deep energy retrofits would be needed to eliminate essentially all CO_2 emissions, so that the buildings sector of 2050 relies exclusively on carbon-free electricity. To do this, we needed projections for the building population in 2050. Our approach, based on standard population projections, is described in detail below. Essentially, the future building stock will consist of the buildings that are here today, minus those that are torn down, plus those that are built between 2010 and 2050. We made one basic, simplifying assumption: Because we find that only very deep retrofits will provide for a carbon-free future, we treat all 2050 buildings as the same within each category. Whether a commercial high-rise building was built in 1970 and then retrofitted in the 2020-2050 time frame, or will be well constructed in 2040, it is represented by the same eQUEST model.

Since we choose carbon-free technologies to power the building sector, we find no greenhouse gas emissions from buildings in 2050. Rather, our result is an estimate of the electric power needed to operate the building sector in a truly sustainable manner. This does result in a peculiarity: in-building combined heat and power (CHP, or cogeneration) is one of the most cost-effective and valuable technologies available today. If biogas can be produced to operate it, it will also have an important role to play in a sustainable future. However, the complexity of including a relatively small amount of CHP in our models led us to exclude it from the 2050 scenarios. The CHP option is discussed further in Section 8.

For the transportation and waste sectors, there will be emissions from residual fuel use, and these must be brought below our reduction targets. There will also be increased electricity consumption, especially in the transportation sector.

EMISSION TARGETS

Deriving a target corresponding to a 90 percent reduction in Scope 1 and 2 emissions by 2050 is straightforward, and the results are presented in Table 3.1. All electric energy is assumed to be carbon free. (The viability of this assumption is discussed in Section 8.) Modest trade-offs are possible between the transportation and fugitive and process sectors, but the split shown below matches our findings. The following sections will show possible strategies for meeting these targets.

The Scope 3 emissions reported by New York City for 2010 were 14.3 million tons of CO_2e, constituting 21 percent of a grand total of 68.6 million tons of CO_2e. These Scope 3 emissions were overwhelmingly airplane fuel at the city's airports, and since airplanes are far from our areas of expertise and many other items such as food production were not included, we have made no attempt to identify reduction paths for Scope 3 items.

Table 3.2: 2010 Population and Employment and 2050 Projections

	2010	2050	Increase
Population	8,180,000	9,350,000	**14%**
Employment	4,610,000	5,940,000	**29%**

Table 3.3: 2010 Citywide Floor Areas and 2050 Projections

Building Type	2010 (Million Square Feet)	2050 (Million Square Feet)
1 or 2 Family House	460	526
Row House	777	889
Low Rise Residential	1,461	1,671
Masonry High Rise Residential	782	876
Window Wall High Rise Residential	72	101
Residential Total	**3,552**	**4,063**
Low Rise Commercial	1,052	1,252
Masonry High Rise Commercial	674	802
Curtain Wall High Rise Commercial	52	62
Commercial Total	**1,778**	**2,116**

POPULATION AND EMPLOYMENT PROJECTIONS FOR 2050

New York City has grown dramatically in recent decades, in both population and jobs, and there is no indication that this trend will abate. Consequently, our projections for energy use and emissions in 2050 must be based on estimates of increased population, employment, and building area. Our projections are summarized in Tables 3.2 and 3.3 and discussed below.

A presentation by the New York Metropolitan Transportation Council[4] provided population and employment forecasts to 2040. Following a suggestion from our advisor at the NYC Department of City Planning, population and employment values were kept constant from 2040 to 2050 rather than continuing to grow. This approach was recommended due to the highly uncertain nature of the forecasts. For example, it is unclear whether linear growth can be sustained given the city's spatial constraints.

Population information was used to determine the residential building area most likely to be present in 2050. Based on 2010 PLUTO data, we calculated a residential area population density of 434 square feet per person. Rather than resolve conflicting trends toward greater or less area per capita, this value was kept constant and used to provide an estimate for the residential building area that will exist in 2050, representing a 14 percent increase from 2010 to 2050.

The window wall high rise residential design is an intrinsically poor design from an energy perspective, and we assumed that building codes will advance sufficiently to ensure that no more are built after 2020. The projections shown in Table 3.3 assume that all residential high rise construction after 2020 is masonry. Except for the window wall case, we assumed equal growth in each building sector. An argument could be made that there will be more growth in taller buildings and less in one and two family homes, but uncertainty in how to allocate differential growth led us to choose the simple approach.

Similarly, employment information was used to determine the commercial building area most likely to be present in 2050. From PLUTO data, we calculated a commercial area employment density of 386 square feet per employee. This value was decreased by 1 percent every five years, as shifting job categories and economic pressure result in smaller workspaces. Even with this slowed growth, we anticipate a 19 percent increase in commercial building area from 2010 to 2050.

The additional residential and commercial buildings in our projections can be accommodated on about 60 percent of the 8,900 acres of vacant land currently in the city[5]. However, the actual area required will be less than that to the extent new construction is focused on high rise buildings, as we expect will happen, and on the replacement of low rise buildings with taller ones.

4. BUILDING SECTOR: ENERGY REDUCTION MEASURES AND SAVINGS

OVERVIEW

Reductions of energy use in and emissions from buildings are achieved by a series of technical improvements called energy efficiency measures, or often, just "measures." These measures make possible reductions in energy use for heating, cooling, and domestic hot water (DHW). To make "90 by 50" possible, it was necessary to reduce loads sufficiently to allow much smaller heating, ventilation, and air conditioning (HVAC) systems to provide comfort using only electricity, and the measures that made this possible are discussed in this section.

The impact of the measures was estimated using the eQUEST models described previously, starting with the models as tuned to the 2010 EUIs and emissions, and adding the measures appropriate to each building. The measures are summarized in Table 4.1 and described in more detail below. The primary result of the modeling was a set of substantially lowered EUIs for the buildings, and reduced total electric energy use and peak demand for each building and for the city as a whole.

Our analysis examined only technical reductions and assumed no significant lifestyle changes take place. We left the thermostats near 70°F in winter and 75°F in summer for both 2010 and 2050, although people could adopt lower interior temperatures in winter and higher ones in summer in response to either prices or greater environmental awareness. We did not include potential savings from telecommuting, which could result in less growth in office space and more intense use of existing residential space in addition to transportation savings. Smart controls such as occupancy sensors can dramatically lower heating and cooling loads, but we have used only standard clock-driven setbacks. We also primarily make use of technologies that are available today, although sometimes in niche markets, but we will point out alternative emerging technologies in our discussions.

Because the infiltration and insulation standards imposed here are rigorous, we also examined a second case where our targets were missed, represented in the building models by greater infiltration and less additional insulation. The corresponding increased electric energy use and demand were found from the adjusted models and are compared to our primary deep reductions case later in this report.

MINIMIZE AIR EXCHANGE LOSSES

Air leaks in buildings occur in numerous places, including cracks in the walls, floors, and ceilings; through gaps around windows and doors; and through leaks in the ductwork. Substantial air sealing and ventilation control, combined with heat or energy recovery systems can alleviate these losses.

Historically, much of residential ventilation has been supplied by air leaks, here described as infiltration. This is a very poor source of ventilation, since airflow varies widely depending on wind speed, indoor versus outdoor temperature, and other variables. In modern construction, every attempt is made to reduce uncontrolled infiltration, so that ventilation can be managed either by windows or by mechanical fan systems. For each 2050 building model, the infiltration rate was reduced to 0.2 air changes per hour (ACH) at atmospheric temperature and pressure (ATP). (For comparison, air infiltration in a passive house is typically no greater than 0.03 ACH – six times less – at ATP). With these low levels of infiltration, healthy air must be maintained by mechanical ventilation.

Achieving 0.2 ACH at ATP from the average building will require a substantial improvement in air-sealing practice. Using today's technology, this upgrade to the city's building envelopes would be carried out by technicians armed with caulk guns, sealing tape, blower doors, and smoke sticks, and would be quite expensive. (See Section 5 on costs.) A more effective possibility is emerging out of work to mitigate leaks in ductwork carried out at Lawrence Berkeley Laboratory[1], in which an aerosol of sealant material is released in a pressurized duct in which the normal exit louver has been sealed. As air passes out through leaks, it deposits sealant in the holes, which thereby become sealed. (Classical auto radiator sealants operate on a similar principle.) For ductwork, the process is now commercially available under license from Aeroseal Corporation. Current practitioners of Aeroseal regarded the use of this approach on entire apartments as a possible future technique, but pointed out that several open issues, including evacuation of both residents and furniture from the apartments, protection of doors, windows, electrical outlets, and other "legitimate" penetrations, and the current high cost for the sealing material[2].

Table 4.1: Building Shell and HVAC Measures

Building Type	Airseal and isolate dwelling units, provide ERV	Airseal building, provide ERV	Lower vision glass to 50% max.	Increase insulation on opaque areas	Triple glaze all windows	Add 3' sunshades to south windows	Mini-split heat pumps	Ground source heat pumps	DHW heat pump operating in conditioned space	Heat recovery for DHW on air conditioners
1 or 2 Family House	✓			✓	✓	✓	✓		✓	✓
Row House	✓			✓	✓	✓	✓		✓	✓
Low Rise Residential	✓			✓	✓	✓	✓		✓	✓
Masonry High Rise Residential	✓			✓	✓	✓		✓	✓	✓
Window Wall High Rise Residential	✓			✓	✓	✓	✓		✓	✓
Low Rise Commercial		✓		✓	✓	✓		✓	✓	✓
Masonry High Rise Commercial		✓		✓	✓	✓		✓	✓	✓
Curtain Wall High Rise Commercial		✓	✓	✓	✓	✓		✓	✓	✓

LOWER VISION GLASS TO 50 PERCENT MAXIMUM

Today's high rise curtain wall and window wall buildings commonly have greater than 50 percent vision glass. While an unobstructed view is a major selling point, this glass leads to high AC loads, greater heat loss in winter, and often to excess glare within the building. We assume that most such buildings will require extensive re-skinning during the next 40 years. For example, GreenSpec reports "Major refurbishment period is 25 – 35 years and includes replacement of insulating glass units, gaskets and capping to frames as necessary."[3] We assumed that at that time, the vision glazing would be reduced to 50 percent or less of the total exposed wall, replaced by spandrel glass that can be well insulated while preserving the exterior appearance.

The proposed reductions in glazing will not compromise existing daylighting. In most circumstances, more than 40 percent glazing does not lead to lowered artificial lighting usage[4], and it is best if the glazing is relatively high in the interior walls, and the light is directed in and up to bounce off the ceilings. Consequently, the addition of spandrel glass on lower portions of the wall will not impact any daylighting advantage in these buildings.

On window wall buildings, we similarly assumed that the vision glass fraction will be lowered to 50 percent during façade rehabilitation. In our model, there was already less than 50 percent vision glass, so we made no change and took no credit in the modeling.

INCREASE INSULATION ON OPAQUE AREAS

Levels of thermal resistance in the opaque portions of the walls of New York City buildings range from the R-2 to R-4 levels typical of uninsulated brick and wood frame structures to values in the range of R-8 to R-10 for modern, code-compliant buildings. Roof insulation is typically higher, with current code requirements of R-20 to R-38 in commercial buildings and R-38 in smaller residential structures. All of these levels are well below what is optimal in a low-energy-use building.

Our 2010 building models incorporated relatively low levels of insulation, chosen to match typical construction and to give EUIs and emissions matching those of the actual 2010 city. These generally fell short of current code requirements. For 2050, all residential buildings were upgraded to R-50 roofs, with R-30 walls on the one or two family house and R-20 walls on other residential buildings. Opaque areas on commercial buildings were upgraded to R-30. Below ground, R-11 was added to the walls. In the computer models, this was easy to do. In real life, there will be complications.

There are legitimate aesthetic concerns related to adding insulation to buildings, but they should not be overstated. First, our assumptions do not require that R-20 be added to each wall, but that enough insulation be added to provide a total resistance of R-20. Second, the insulation can most easily be added to the building's exterior, but when this is not appropriate (as for any architecturally pleasing front façade), insulation

Figure 4.1: Standard EPS and equivalent vacuum foam R-39 insulation.

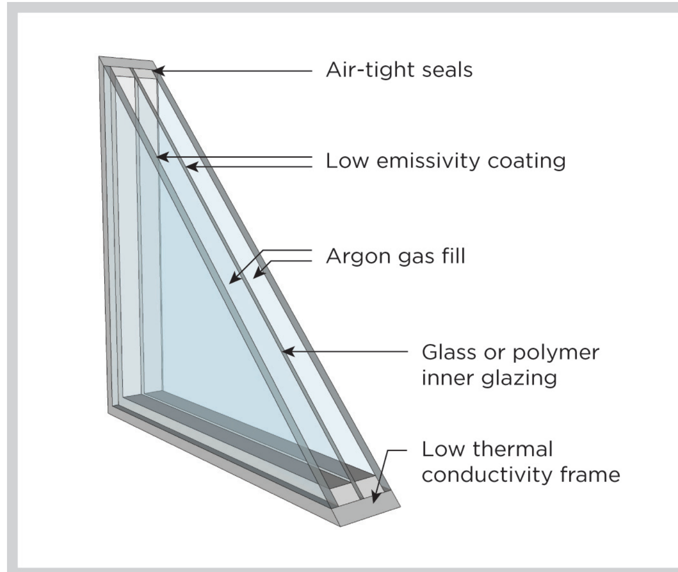

Figure 4.2: Details of triple-glazed window.

can be added to the interior of the wall. Finally, R-20 and R-50 represent average values, and some buildings will be below, and others, above average. Discussion of these three points follows.

A total thermal resistance of R-20 does not necessarily require a bulbous addition to the building. A typical building might have R-8 walls already, so an additional R-12 will be needed. Standard XPS foam board is R-5 per inch, so that would require a 2.5-inch layer to be added. However, polyisocyanurate is currently available at R-7 per inch, requiring slightly less than 2 inches. But these are examples of what is readily available today in builders' supply stores. Aerogels are now available at a premium price that offer more than R-10 per inch[5]. Dow has an available vacuum foam insulation rated at R-39 per inch[6], greatly reducing the required thickness, as shown in Figure 4.1.

Where would this insulation go? The exterior is preferable when possible. In this case, some form of surface material, whether stucco or a part of a factory-prepared modular system, would be required to provide physical integrity and to shed water. Since many, if not most, New York City buildings are constructed up to the legal limits of lot lines and setbacks, challenges will arise. Some of these challenges have already been met by the Zone Green[7] changes to the NYC Zoning Resolution, which now permit up to 8 inches of insulation to project over legal setbacks and city lot lines, as long as the insulation is effective. Also, this insulation no longer results in greater floor area for taxation purposes. Property lines present substantially greater challenges.

It is also important that additional insulation not be allowed to cover façade deterioration, since the original façade will no longer be visible. The addition of insulation must be accompanied by careful inspection of the condition of external masonry, with repair preceding the addition of insulation, and rigorous standards maintained to ensure that water penetration beneath the insulation is minimal and the cavity well drained and ventilated.

Owners of brownstone town houses and many other buildings with decorative facades will not want to utilize external insulation, but other options exist, starting with additional interior insulation. Interior insulation must be evaluated carefully, as not all masonry can withstand the increased temperature cycling that will occur if it is isolated from the interior[8].

Also, these target EUIs and R-values are averages across the entire city, and if some buildings go beyond these average requirements, others can lag behind. For example, if a building does not meet these insulation targets, more electricity will be required to provide heating and cooling for that building. Since electricity prices will certainly rise, a somewhat higher heating bill may be the price for a beautiful front façade left untouched.

U-VALUE AND R-VALUE

The ability of a material to conduct heat is measured by its "U-value," where U=2.0 indicates that 2.0 British thermal units (Btus) of heat will flow through one square foot of the material (at a specified thickness) each hour for each degree of temperature difference across the object. The "R-value" measures thermal resistance and is equal to 1/U, so an object with U=0.5 would have R-2.0. R values are commonly used for walls and insulation, and U values for windows and other glazing, but either is a valid description of heat conduction in any material.

INCORPORATE TRIPLE GLAZING

Until the 1980s, windows in New York City were almost all single glazed. (That is, they consisted of a single layer of glass.) A single-glazed window has a whole window average

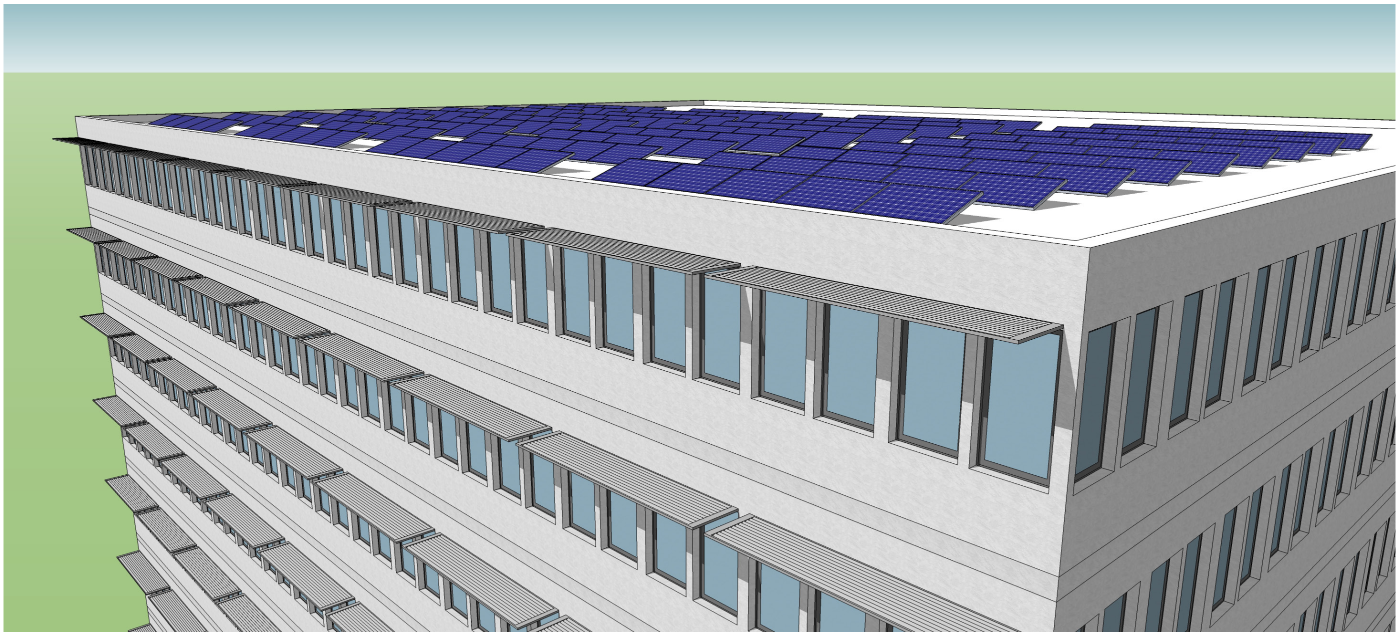

Figure 4.3: Upper floors of 2050 High Rise Masonry Commercial building, showing sun shades.

U-value of about 1.0, transmitting far more heat than the walls of even those poorly insulated buildings. Partly in response to the oil crises of the time, building standards were stiffened, and various financial incentives made available. In the space of 20 years or less, almost all windows were replaced with double-glazed models, and double glazing became the standard for curtain wall construction as well. An average double-glazed window with a thermally broken aluminum frame has a U-value of about 0.50, although high-performance versions with fiberglass frames (for windows) and carefully constructed mullions (for curtain walls) can be as low as U=0.32.

However, to bring buildings down to the performance range envisioned in this study, another step is needed: triple glazing. This can be accomplished either by adding another layer of glass or, for lower cost and weight, by adding a layer of polymer film between the two layers of glass. (This provides all the thermal advantages of a glass layer with a much smaller increment in weight, but there are other important technical differences.) With a high-quality triple-glazed window or curtain wall, U=0.20 is readily achievable, and that is the glazing represented in all 2050 building models. The technology is illustrated in Figure 4.2.

We consider this technologically conservative; it is a known and easily obtained technology today, although rarely used in the U.S. due to somewhat higher cost and a lack of familiarity. Transparent aerogels[9] are in development that will allow U-values as low as 0.05 (R-20), and are likely to be available well before 2050, but we have not used them. Nor have we relied on electrochromic glass[10], for which the reflectivity can be controlled electronically to facilitate daylighting and lower AC loads.

ADD SUNSHADES TO SOUTH WINDOWS

Sunshades control the amount of direct sunlight allowed to pass through a building's windows. By deflecting heat and glare, sunshades can reduce cooling equipment loads, leading to decreases in cooling energy cost. The size and placement of the sunshades is highly dependent on the geographic location of the building, including the direction that the windows face. In the Northern Hemisphere, sunshades over south-facing windows block sunlight in summer months when the sun is higher in the sky, reducing heat gain into the building. In winter months, when the sun follows a lower path in the sky, heat gain through the windows remains substantially unaffected. For our 2050 models, sunshades 3 ft. in length were installed horizontally, directly above the south-facing windows, as shown in Figure 4.3 for the high rise commercial building.

These static shades, used only on the south-facing windows, are the simplest form of solar gain control. Shades can be purchased today that can be adjusted to match the seasons or even the time of day. Vertical blinds offer advantages in some cases, venetian blind configurations facilitate daylighting, and blinds appropriate to east- or west-facing windows can also be used. None of these more complex options were employed in our models.

THE INTERACTION OF ARCHITECTURAL MEASURES

The levels of change we are examining in our models will raise eyebrows. Each of the proposed measures above calls for a level of insulation, air sealing, or glazing that is not currently regarded as worthwhile. If the measures were regarded in isolation in a typical contemporary building, there is truth to that. There is no point in adding insulation up to the R-20 level (over R-10) if heating and cooling loads driven by infiltration, ventilation, and equipment inefficiency are left at their current high levels. The last R-10 increment of insulation will do very little to the overall heating or cooling load, since the heat will be leaving or entering the building through those other modes.

However, the only path to a truly low-energy building is to reduce all loss pathways. When this is done, and all routes for unwanted heat loss or gain are treated as a unified whole, then each of the measures considered here will still make significant contributions to energy use reduction, even at these "extreme" levels.

Because of the uncertainty of economic data, from measure costs to fuel prices, we have made no attempt to optimize the relative levels of implementation of these measures economically. We have, rather, leaned heavily on the techniques and levels of implementation developed in the Passive House[11] program, since these have been shown to result in comfortable, livable, and cost-effective structures when properly implemented.

HEAT RECOVERY VENTILATION

The ASHRAE 62.1 Ventilation for Acceptable Indoor Air Quality standard[12] requires certain minimum airflow rates based on building area and occupancy. For our building models, we settled on air exchange rates double those of the ASHRAE standard. For the residential buildings, the forced airflow rates were modeled as 0.12 cfm/sf and 10 cfm/person. For commercial buildings, the flow rates were modeled as 0.24 cfm/sf and 20 cfm/person. For some residential settings, lower rates would be regarded as acceptable[13], but since (as we will see) this level of ventilation allowed quite low HVAC loads, we maintained the same rates in all buildings.

Simply bringing those levels of fresh air into the buildings would impose substantial loads in both winter and summer. To minimize loads, energy recovery ventilation (ERV) was implemented in our models. During the winter months, heat and desirable humidity was used to precondition the incoming cold, dry air. During summer months, the incoming air was precooled and dehumidified. The system modeled here operated with an overall efficiency of 75 percent. Energy recovery ventilation in residential settings is commonly based on plate heat exchangers, especially in the single-apartment sizes we envisioned in our modeling, while larger commercial systems use an enthalpy wheel. We used the wheel in the computer model for all buildings for simplicity, but it gave essentially the same thermal savings and electric usage as a plate heat exchanger would have in the residential buildings. The operation of both devices is shown in Figures 4.4 and 4.5.

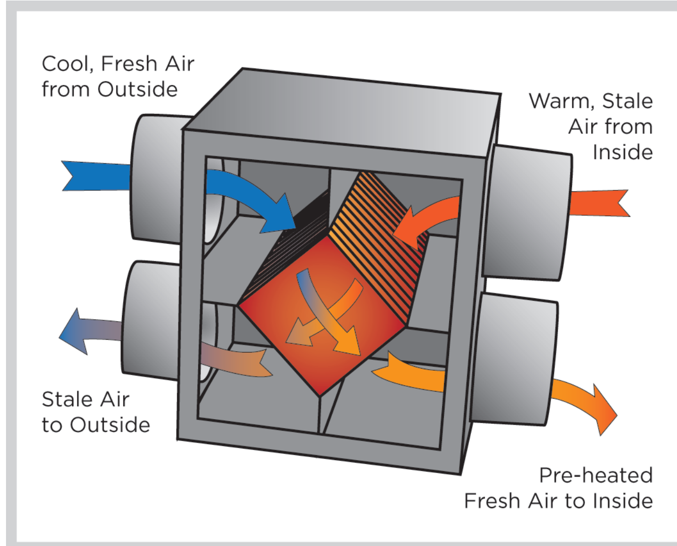

Figure 4.4: Heat recovery ventilation warms outdoor ventilation air on the way in and is primarily used in residential settings.

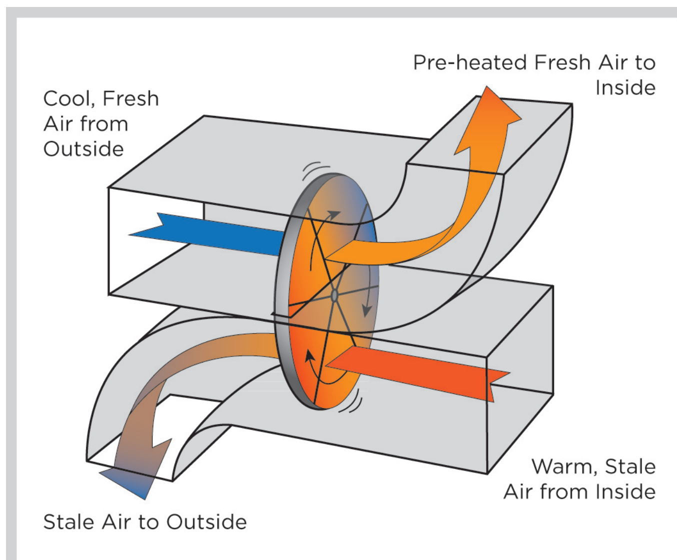

Figure 4.5: Energy recovery ventilation captures both heat and moisture, to retain humidity levels, and is primarily used in commercial buildings.

MINI-SPLIT HEAT PUMPS FOR MOST RESIDENTIAL HVAC

Window and sleeve air conditioners are notoriously leaky. An earlier Urban Green Council study[14] found that the heating bill associated with making up for air leaks around air conditioners in the winter was comparable to the electric bill for air conditioner usage in the summer! Leaks can be prevented by systems that separate the condenser unit, which is outdoors, from the evaporator, which is indoors, connecting them only by tubes for the refrigerant and condensate water. As air conditioners, these are standard systems for centrally cooled single-family homes, and are available in apartment sizes, colloquially called "mini-splits." However, they can also be redesigned to operate as heat pumps in the winter, with the role of the condenser and evaporator reversed. One manufacturer[15] has a broad line of these machines, which we used as examples for our models, but many others will undoubtedly become available soon. Not only does this technology allow complete electrification of heating as well as cooling, but it also provides

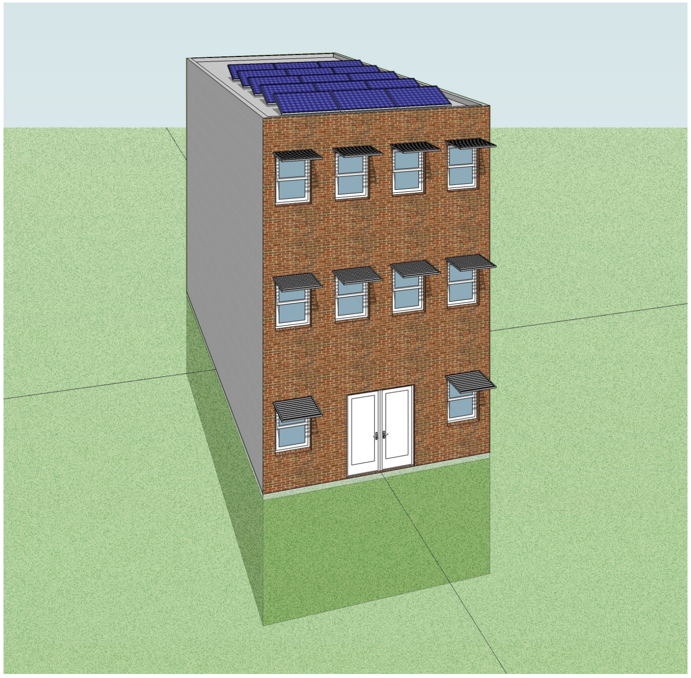

Figure 4.6: 2050 Row House

a way to remove residential heating from central building services and put it in the control and at the expense of the resident — the most error-free way to minimize heating waste.

Because of our substantial load reductions, it is possible in our models to heat and cool apartments, houses, and row houses with equipment with much lower capacity than is currently in use. We chose a cooling energy efficiency ratio (EER) of 16 Btu/watt-hour and a heating coefficient of performance (COP) of 3.6, performance that is available today, although at a premium price. An area where development will have to occur is in the capacity of available systems, as deep retrofits such as these will open a market for apartment systems with capacity comparable to or less than that used in a single window unit today.

Installation of mini-splits in some developing countries has resulted in buildings festooned with an ugly collection of condensers, but this is not a necessary part of this technology. A variety of shapes and implementations for multifamily buildings are possible. Downsizing will permit development of well-designed, well-sealed, and well-insulated mini-splits that will fit into the sleeves currently holding large air conditioners. Alternatively, condensers can hang on a rear or courtyard wall, while evaporators are distributed in the apartment where needed.

Our models use mini-splits for heating and cooling in all one and two family homes, row houses, low rise residential buildings, and the high rise window wall residential building, which is already heated and cooled by inefficient packaged terminal air conditioners (PTACs), which these units will replace.

WATER-SOURCE AND GROUND-SOURCE HEAT PUMPS

Since our deep-efficiency retrofits have lowered building loads in the models dramatically, the next step is to use high performance building systems to provide heating and cooling. Consequently, our models provide these services to commercial buildings and the high rise masonry residential buildings with ground-source heat pumps, circulating water through deep vertical wells and depositing the building's excess heat in the earth during the summer, while retrieving it to provide space heat in the winter.

Open loop systems, where the circulating fluid comes in direct contact with the earth, are best in dense urban environments because of their high capacity per area for a well field. This technology is now well known in New York City, having been implemented at the Center for Architecture[16], the General Theological Seminary[17], and other buildings. It is still expensive, and drilling the wells is disruptive, but there are few serious technical barriers to its deployment. Practical barriers remain.

The main practical barrier with open loop systems is that site specific geological conditions, unknown until the drilling of a test well, have a major influence on the capacity and maintenance requirements of the well field. Lack of water intrusion in the well or unstable or sandy earth conditions can lead to overheated wells or sand intrusion into the building system. There are techniques for remedying these conditions, such as drilling more wells or supplementing the system with another source.

Another barrier is the reluctance of the NYC Department of Environmental Protection to permit drilling anywhere near the city's water tunnels. Another is the extensive underground infrastructure of water supply pipes, sewers, subway tunnels, and wire conduits. However, a well requires a space of only a few square feet in, for example, a sidewalk, and as experience is gained, the subsurface is better mapped, and authorities gain confidence in the accuracy of drilling, relaxation of these restrictions must be a priority. Ground source heat pumps are readily modeled in eQUEST, although the simulation does not look carefully at the subsurface heat exchange.

Distribution makes use of existing piping systems for all two- (or four-) pipe systems, replacing or supplementing existing radiators or convectors with fan coil units to provide cooling capability. Two-pipe steam can be converted directly to hydronic with partial[18] or complete[19] replacement of the distribution system, while for one-pipe steam systems, the pipe must be replaced or (if in very good condition) a pipe added. The substantially lower loads allow for considerable downsizing in pipe and radiator sizes.

Optimal design of ground-source heat pumps calls for the heating and cooling loads to be balanced, so there is no long-term heating or cooling of the earth, which would be a problem both for the building causing the change, and for neighboring buildings also using the technology. Consequently, the best way to design such a system is to size both heating and cooling for the smaller of the two loads, and make up the remainder of the larger load with a separate system. For residential buildings, which generally have larger heating loads, this would require either an air-source heat pump or electric resistance heat. For commercial buildings, it would require an additional central air conditioner with a rooftop cooling tower. While this path is more likely to be followed in reality, we did not take the time to model it, since reducing the capacity of the ground-source system will almost certainly cover the cost of the make-up heating or cooling system, and the change in efficiency will not be large.

AIR-SOURCE HEAT PUMPS FOR DOMESTIC HOT WATER

Domestic hot water (DHW) needs in New York City are commonly met by burning a fossil fuel, or in some cases, with an electric resistance hot water heater. Neither technology will be useful in the future envisioned in "90 by 50." A technology now gaining commercial acceptance, called an air-source heat pump (ASHP), withdraws thermal energy from the air surrounding the device and uses it to provide DHW[20]. Because the water is heated only to a modest 124-130°F, the machines operate at a COP of 4.0[†]. They are assumed to be located in the conditioned space, and as a result they provide "free" cooling and dehumidification in summer, lowering cooling loads substantially, while adding to the heating load in winter. These interactions are accounted for in the eQUEST modeling, and these units supply DHW in all buildings, except for that supplied by the technology in the next paragraph. Since each apartment has its own hot water source, recirculation losses are eliminated and, as for heat, the apartment owners are financially responsible for their own consumption.

† COP is "Coefficient of Performance", the ratio of thermal energy supplied by the device to the electrical energy used to power it, when operating in a steady state at full load.

HEAT RECOVERY ON HEAT PUMPS FOR COOLING SEASON DHW

An appropriate heat exchanger allows one to harvest heat from the condenser of the AC system during summer cooling and apply it directly to DHW. Since this heat is available using only the energy for a circulation pump, it is used first for DHW when available, with the ASHP providing residual demand. These systems are commercially available in Europe today, and we have made use of them in all buildings.

SOLAR THERMAL COLLECTORS

The feasibility of installing solar water heaters (SWHs) was explored with RETScreen[21], an Excel-based clean energy project analysis software tool. Rooftop SWHs were considered for each building model. Given the environment of a carbon-free electric economy and the presence of other sources of efficient heat recovery for DHW utilized by the models, solar photovoltaics helping to feed the air-source heat pumps were a better use of rooftop area. (This would not be the correct conclusion in today's energy economy, which is dominated by fossil fuel combustion.)

APPLIANCES AND INTERNAL LOADS

2010 internal electrical and gas loads were discussed in Section 2. For 2050, many opportunities to lower those loads were exploited, and this section provides a summary of those reductions.

Table 4.2: Annual Residential Equipment Usage

Equipment Type	2010 (kWh/ Dwelling Unit)	2010 (MMBtu/ Dwelling Unit)	Approx. Reduction	2050 (kWh/ Dwelling Unit)
Refrigerator	789		50%	400
Clothes Washer (Electric)	95		25%	71
Dishwasher (Electric)	83		25%	62
Personal Computer	273		0%	273
Color Television	217		25%	163
Other Electronics	81		0%	81
Other Miscellaneous	865		29%	615*
Condensing Dryer (Gas)		2.36	75%	173
Induction Stove (Gas)		3.54	52%	494
Total	**2,403**	**5.90****		**2,332**

* Includes replacement of cable boxes for 250 kWh savings
** Fuel use in 2010 equivalent to 1,730 kWh; 0 kWh in 2050

For lighting, data from the Con Edison study[22] provided 2010 baseline loads and specified how many lamps were linear fluorescent and how many were "screw in." Taking 2010 linear fluorescent lamps at 70 lumens per watt, compact fluorescent lamps at 75, and incandescent lamps at 15, a total number of lumens per dwelling unit or per square foot could be developed from an assumption on how many "screw in" lamps were incandescent. 2050 lighting power densities were then developed by requiring the same lumen density, but supplying it with 100 lumen-per-watt fixtures without specifying the type (high-performance fluorescent, light-emitting diode [LED], etc.). Annual lighting energy use was also reduced by 20 percent to account for dimming, bi-level, and occupancy controls. For the residential buildings, an assumption that 70 percent of "screw-in" lamps were incandescent led to a 73 percent reduction in lighting energy, while for commercial, an assumption that 50 percent of the much smaller number of "screw-in" lamps were incandescent led to a 46 percent reduction. A similar treatment of external lighting (the only "external load") led to 66 percent reductions for residential buildings and 49 percent reductions for commercial buildings.

The treatment of "miscellaneous equipment" in the residential sector is shown in Table 4.2. All the reductions are based on known technical improvements, most of which are available in the market today. Gas stoves and dryers are replaced with electrical induction stoves and condensing gas dryers.

Table 4.3: Annual Commercial Equipment Usage				
Equipment Type		2010 (kWh/sf)	Approximate Reduction	2050 (kWh/sf)
Refrigerator	Reach-in	1.00	50%	0.50
Refrigerator	Walk-in	3.49	50%	1.74
Food Service		2.34	25%	1.76
Office Equipment	Personal Computer	0.35	0%	0.35
Office Equipment	Server	0.24	25%	0.18
Office Equipment	Monitor	0.40	25%	0.30
Office Equipment	Printer / Copier	0.10	25%	0.08
Office Equipment	Other	0.36	25%	0.27
Total		**8.28**		**5.18**

Commercial equipment energy use reductions are shown in Table 4.3. The food service reductions are based on current state-of-the-art equipment. The reduction estimates for office equipment are not based on market-ready products, but instead on physical data. The energy use of computers per calculation has been shown to be halved every eighteen months[23], a reduction far more dramatic than our assumptions. At a simpler level, many desktop computers use 50-60 percent of their full-on power when nominally asleep due to faulty settings, despite much more stringent specifications.

PHOTOVOLTAICS WHERE POSSIBLE

Solar energy is perhaps the most abundant, yet underutilized, of all potential renewable energy sources. Even in the Northeast where solar insolation is limited, solar energy can be harnessed to meet the needs of both residential and commercial electricity users. The National Renewable Energy Laboratory[24] estimates the average solar insolation in New York City as approximately 4.34 kWh per square meter per day for the best deployment of a stationary system, a flat solar panel tilted at an angle equal to latitude. This resource was used to reduce building loads in all our models.

Solar panels consist of a number of photovoltaic cells that convert solar radiation into useful electric power. Solar panels were added to the rooftops of each of our building models for 2050, based on the technical specifications from SunPower Solar's E20 Series. These monocrystalline silicon panels have a 20 percent module efficiency — the highest efficiency available

Table 4.4: Electricity Use and Energy Use Intensities in 2050 Buildings						
Building Type	Area (sf) Above Ground	Building Energy Usage		Impact of Photovoltaics*		
		Building Electricity Use (MWh/yr)	Building EUI (kBtu/sf)	PV Production (MWh/yr)	Net Electric Use (MWh/yr)	Net EUIs (kBtu/sf)
1 or 2 Family House	1,352	9.0	22.7	7.2	1.7	4.4
Row House	1,992	14.5	24.8	8.4	6.1	10.5
Low Rise Residential	8,558	61.4	24.5	27.5	33.9	13.5
Masonry High Rise Residential	122,972	578.0	16.0	80.1	497	13.8
Window Wall High Rise Residential	184,793	1,020.0	18.8	71.8	948	17.5
Low Rise Commercial	15,170	194.8	43.8	100.2	94.6	21.3
Masonry High Rise Commercial	229,249	2,088.0	31.1	179.1	1,909.0	28.4
Curtain Wall High Rise Commercial	192,808	1,757.0	31.1	121.6	1,635.0	28.9

* Photovoltaics added to 50% of buildings citywide

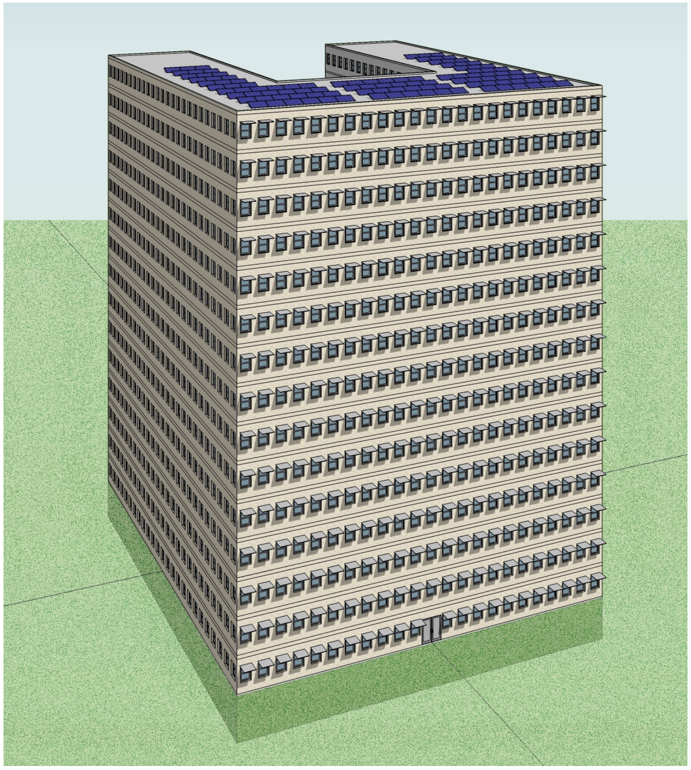

Figure 4.7: 2050 Residential High Rise (Masonry)

on the market today. As solar panels produce direct current (DC) power, an inverter was required to convert to usable alternating current (AC), at a conversion efficiency of approximately 90 percent.

Solar collectors were added, covering up to 60 percent of the available rooftop area to allow for machine rooms, fire department access, and other uses. We assumed that each building model had unshadowed access to the solar resource, but that only half the actual buildings of each type had unshadowed access to sunshine, reducing the scaling factor by 50 percent. For the buildings with solar photovoltaics, the electric energy requirements were reduced by as little as 7 percent for the high rise commercial curtain wall model, and as much as 81 percent for the one or two family house. In Table 4.4, the solar power produced in each building was kept separate from the loads of the building and the total solar energy produced is counted against the electrical load for the entire city. Even for the smaller buildings, the notion of "net zero" was not explicitly pursued. The one or two family house came closest to achieving it. The resulting city-wide capacity and generation is about 25 percent greater than that found by the New York City Solar Map[25] because our collectors are substantially more efficient than the 2010 devices they assumed would be installed.

FINAL BUILDING SECTOR ELECTRICITY REQUIREMENTS

The building models were run again with these measures implemented, and the resulting EUIs are presented in Table 4.4.

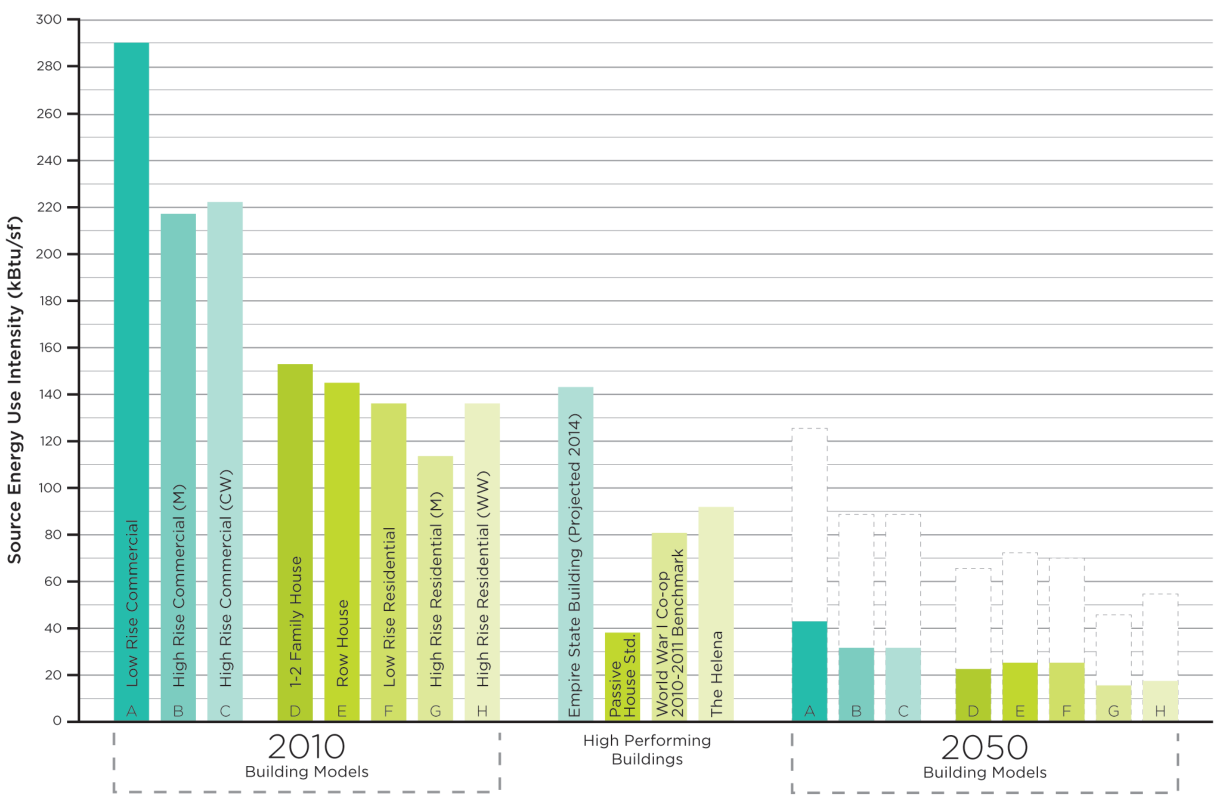

Figure 4.8: Source EUI comparisons of 2010 modeled buildings, current high-performing buildings, and modeled 2050 buildings. For 2050, solid bars represent EUIs with carbon-free electricity and dashed outlines represent EUIs of 2050 buildings with electricity from the 2010 fuel mix.

Electric energy use is shown first for internal building usage, as if there were no photovoltaics (PVs) on the roof, followed by PV production for that building (assuming it is one of the 50 percent that received PVs), followed by the net energy the building demands from the grid in one year.

The 2050 EUIs shown are calculated at 3,412 Btu/kWh, following our discussion of source energy in Section 2. That is, because the electricity is assumed to be carbon-free, we treat site energy and source energy the same in 2050. Theoretical objections could be raised that considerable thermal energy is discarded in either photovoltaic cells or nuclear reactors, but since our primary concern is greenhouse gas reductions, we do not pursue this issue in this work.

The building EUIs are low, comparable to passive house values, as should be expected. (They are sometimes lower than passive house values because the ground source heat pumps are so efficient.) These low loads are key to the practicality of ground source heat pumps in the dense urban environment. The one or two family house comes close to being net zero, which means that in the real world, a fair number of such buildings should actually be able to achieve this target.

The electric energy and demand needed to power the buildings were then summed across building sectors. Discussion of those results is presented in Section 8, Conclusions.

5. BUILDING SECTOR: COST ESTIMATES

APPROACH

There is something quixotic about estimating costs for a project that extends at least 37 years into the future. Nevertheless, getting a sense of whether the project is so outrageously expensive it should not be attempted or whether it falls within the realm of the possible is necessary for the idea to be taken seriously. Consequently, we developed costs for the proposed measures on a per unit basis (per square foot of floor area, per apartment…) and used them to develop overall estimates for applying all appropriate retrofits to each building type. These estimates were then scaled up to provide an overall estimate of the cost to retrofit the entire city. Finally, we estimated the anticipated savings resulting from the retrofits to find what portion of the entire project might be paid for by those savings, within the large uncertainties associated with such a long-term, large-scale effort.

Although we have at various points assumed that currently cutting-edge technologies will become more commonplace, we have used today's prices for these technologies in estimating costs. Making any other assumption opens up too many possibilities for meaningful analysis. Clearly, many things can change over the next two or three decades, and the costs of some measures may drop dramatically. Conversely, it is very unlikely that the costs of basic retrofit technologies will increase.

There are two types of measures used in our analysis, and we priced them differently. The first type of measure is one that would be done only for its energy value, and would not be done in the course of normal building maintenance. Adding insulation and carrying out air sealing are two examples of this type. For these measures, we included the entire cost of carrying out the work.

However, many other measures are modifications to actions that would be required to keep a building in good repair regardless of other considerations. Windows, heating systems, and many other items wear out and must be replaced, especially when considering a 37 year time horizon. For these measures, we included only the incremental cost above that of a standard item. For example, when examining the cost of converting to ground source heat pumps, we assumed that at least the conventional boiler would have to be replaced over the same period, so we count as the "cost of the measure" only the incremental cost above this normal maintenance item. Key building components that will be replaced or undergo major rehabilitation in many buildings in the decades before 2050 include:

- Windows, window walls, and curtain walls;
- Boilers, burners, and HVAC controls;
- PTACs and air conditioners; and
- Domestic hot water (DHW) equipment.

The cost-estimating group of Lend Lease (US) Construction LMB, Inc., provided us with the cost estimates presented in this section. Because Lend Lease worked from our rapidly evolving descriptions of buildings and measures and did not have control over the final product, all errors are our responsibility. The estimates were reviewed by some members of our advisory group and other knowledgeable professionals, and with a few exceptions, they agreed that the estimates were "within five or ten percent" or "in the ballpark", although everyone agreed that the uncertainties are large in an exercise like this. We have altered a few of the estimates in response to some particular comments, as will be discussed below. The estimates are summarized below in Table 5.1, and a detailed accounting is included as Appendix B, Tables B.1 and B.2.

COST ESTIMATES BY BUILDING TYPE

Table 5.1 summarizes the costs of carrying out the retrofit options used in the building models for each building type. (The details are developed in the following section.) The costs were determined for the modeled buildings and would vary widely

Table 5.1: Costs of Proposed Retrofit Measures

Building Type	Incremental Retrofit Cost	Cost/Unit	Cost/sf
1 or 2 Family House	$26,110	$26,110	
Row House	$31,670	$15,840	
Low Rise Residential	$179,700	$19,960	
Masonry High Rise Residential	$4,440,000	$37,950	
Window Wall High Rise Residential	$4,205,000	$29,610	
Low Rise Commercial	$554,900		$36.58
Masonry High Rise Commercial	$6,970,000		$30.41
Curtain Wall High Rise Commercial	$11,180,000		$58.00

over the range of buildings included in each category, but just as modeled energy savings for our specific buildings are taken as representative of each building class, so these costs will be regarded as a first-pass estimate of costs for each building class. In each case, the incremental cost, after credit for normal replacements, is presented.

COST ESTIMATES BY MEASURE

The unit costs of both conventional and innovative measures are presented in Table B.1 for each building type. The total cost of all appropriate measures in each building are presented in Table B.2. Air sealing ranged from relatively inexpensive, $2.30 per square foot for the high rise buildings, to $6.00 for the low rise residential, to $16.00 for the low rise commercial building. Lend Lease had developed the prices under the condition of one-tenth air change per hour (0.1 ACH) at standard conditions, but knowledgeable reviewers with residential experience regarded that as a very difficult target, requiring detailed and expensive work. We accordingly backed the requirement and modeling datum off to two-tenths of an air change per hour (0.2 ACH), doubling the infiltration in all buildings, but left the cost estimates at the original values.

Adding insulation to bring opaque areas up to R-20 in residential buildings, with R-50 roofs, and to R-30 everywhere for commercial buildings, was estimated at $2.60 per square foot of elevated opaque surface (rather than floor area). The insulation estimates were based on adding external insulation and sheathing. The total cost of these items was used as our cost, since they would not normally be undertaken in the course of normal maintenance.

Triple glazing costs were derived by subtracting the cost of a necessary double glazed replacement from the cost of the proposed triple glazed item, on a per-square-foot-of-glazed area basis. For example, low rise residential buildings cost $35/sf for double glazing and $50/sf for triple glazing, so the incremental cost was $15 per glazed square foot. Comparable figures for the high rise windowed buildings were $65 and $90/sf and $75 and $100/sf for the window wall. The curtain wall re-skinning was estimated at $120 per vertical square foot for a standard replacement, and $150/sf for triple glazed, leading to an incremental cost of $30 per vertical square foot.

Residential heat recovery ventilation included capping existing kitchen and bath ducts and installing new transfer ducts to bring fresh air to bedrooms and exhaust ducts to remove air from kitchens and bathrooms. This came in at $3.00/sf for the larger buildings and $1.50/sf for the single family house and row house.

The three low rise residential buildings were outfitted with mini-split heat pumps, assuming one system per unit. Because window wall high rise residential buildings are currently constructed with packaged terminal air conditioners (PTACs), we modeled and Lend Lease developed prices for replacement of the PTACs with high performance mini-split heat pumps in each apartment. The alternative, a central system with a ground-source heat pump, would have required the installation of the entire hydronic distribution system, at great expense and requiring core drilling.

The other three high rise buildings were retrofitted with ground source heat pumps, making use of hydronic distribution already in place when possible. Lend Lease priced the geothermal system at $17/sf for the entire system minus the hydronic distribution. Based on a recent New York City steam-to-hydronic conversion[1], we have added $5/sf to cover partial to full replacement of piping. In all cases, the credit for the replacement of the existing systems reduced the projected cost of the measure substantially.

The heat pump and heat-recovery-based hot water systems are all based on currently available, although not commonly deployed, technology.

COSTS TOTALED FOR NEW YORK CITY

The cost estimates above were scaled up to develop an estimate of the total cost of retrofitting New York City using the ratio of total floor area for each building type to the floor area of that building model, as was done to calculate city wide energy consumption and emissions. Using our building area projections for 2050, we found a total prospective cost of $167 billion in 2012 dollars, with no discounting. Spread evenly over the 35 years from 2015 to 2050, this amounts to $4.8 billion per year, roughly seven percent of the city's municipal budget or four-tenths of one percent of the gross municipal product. Put another way, it corresponds to an investment of about $585 per year for each of 8.2 million New Yorkers now in residence. This cost estimate is based on 2010 construction costs, and for many technologies, there is every reason to expect technical advances and market pull to reduce prices, in some cases dramatically, over time.

COST EFFECTIVENESS

Many of the measures proposed are cost effective today due to savings in fuel and electric usage and would be widely implemented were it not for various market imperfections. But several others (for instance, the substantial insulation additions)

Table 5.2: Financial Savings in Buildings

Commodity	Unit	Cost/Unit
Commodity Costs, 2010		
Electricity	MWh	$230.00
Gas	Dekatherm	$13.30
Oil (#2, 4, & 6)	Gallon	$2.90
Steam	Million Btu	$25.00
Total Energy Bill		**$18.4 Billion**
Commodity Costs, 2050		
Electricity	MWh	$250.00
Total Energy Bill		**$10.8 Billion**

are not, at least using currently acceptable five-year payback periods. We did not separate out savings for individual measures or in individual buildings, but did perform a rough estimate of the overall expected savings.

First, the total project cost of $167 billion was allocated uniformly (in constant 2010 dollars) to the 35 years from 2015 to 2050. We then determined a value for the total cost of fuel and electricity used in the city in 2015 from current costs, and a value for the electricity to be used in 2050 from a hypothetical 2050 cost. Both are shown in Table 5.2.

We found that a reduction in costs of 1.5 percent per year would reproduce this reduction over 35 years, and ascribed that annual reduction to the investment made the year before. We assumed that each investment would continue to produce savings for 30 years, after which some substantial investment would be required to repair or replace the measures. The result was net savings due to the investments made over the 35 year period of $148 billion (with no discounting). This amounts to 89 percent of the total, undiscounted capital cost.

However, it is not realistic to base decisions on crude totals of costs and savings. Money in the future is worth less than money in the present, independent of inflation, and decisions must be based on discounted values of future savings and payments. We accordingly calculated a discounted present value for the savings of $87 billion in 2012, based on a three percent constant dollar discount rate[2]. Also, the present value of the uniform capital outlays, discounted at three percent, is $94 billion. So the discounted present value of the savings corresponds to 93 percent of the discounted present value of the capital cost.

So under our baseline assumptions, "90 by 50" is very close to paying for itself, using standard, long-term economic methods[2]. These methods, which are accepting of payback periods measured in decades, are not familiar to building owners but commonly used to evaluate the construction of power plants and other large infrastructure projects.

However, any realistic scenario for the future will violate our baseline assumptions in three ways: fuel prices will rise faster than inflation, due to either market forces or some form of carbon tax, the costs of many of our proposed measures will fall as they become standard practice, and inclusion of our measures in new construction will be far less costly than implementing them as retrofits. Under any plausible mix of these factors, "90 by 50" will be either cost neutral or a net economic gain when costs and benefits are aggregated over the entire city.

COMMENTS ON COST ANALYSIS

There is no question that these are intimidating numbers. However, it is also important to keep in mind that while some of the measures considered here are not commonly employed today, the time scale on which we are working leaves open two possibilities that can dramatically shift current attitudes:

- The seriousness and potential costs of not acting will become ever more clear, and
- Technological advances will provide either lower costs for the technologies we have examined, or will provide alternate technologies that will do the same job for less.

For comparison, the reconstruction of the Tappan Zee Bridge will cost $10 to $20 billion, depending on options, and the reconstruction of the World Trade Center is costing in the neighborhood of $5 billion. Current, very preliminary estimates of the cost of the damage from hurricane Sandy are in the range of $50 billion, incurred in one tragic event that may well be repeated regularly. The cost estimates presented here are necessarily preliminary and tentative, but since the capital invested would, in the long term, be returned in fuel and energy savings, "90 by 50" does not appear to be a fanciful dream, but rather, an achievable and worthwhile goal.

6. TRANSPORTATION SECTOR

APPROACH AND METHODS

Although our primary focus and in-depth analysis is on the building sector, it is necessary to address transportation for its significant (21 percent) contribution to New York City's greenhouse gas (GHG) emissions. This section provides rough estimates of potential reductions based on fuel switching and foreseeable efficiency improvements. To account for the residual demands for fuel-powered vehicles, this study has been structured so that most of the emissions remaining after the citywide 90 percent reduction are allocated to the transportation sector. Significant improvements to New York City's transportation infrastructure will still be required to meet this target.

To develop a 2050 scenario with greatly reduced emissions, we first used 2010 data to estimate total passenger-miles-traveled (PMT, moving one person one mile) and ton-miles-traveled (TMT) for each mode of transport. The resulting PMT and TMT were then scaled up to 2050 levels in proportion to our

Table 6.1: 2010 Transportation Emissions by Mode

2010 Mode	Fuel Type	Fuel Unit	Fuel Consumed	Emissions $MgCO_2e$	PMT/TMT* (Millions)
Buses					
Transit Buses	Compressed Natural Gas	Gigajoules	1,420,989	78,637	299
Transit Buses	Diesel	Liters	188,631,878	509,784	2,161
Nontransit Buses	Diesel	Liters	7,545,275	20,391	86
Heavy Trucks					
Heavy Trucks	Diesel	Liters	326,200,350	881,807	5,073
Solid Waste Transport Trucks	Diesel	Liters	28,064,413	75,797	436
Light Trucks					
Light Trucks	Diesel	Liters	35,234,181	95,080	214
Light Trucks	Gasoline	Liters	440,373,688	946,168	1,696
Passenger Cars					
Passenger Cars	Diesel	Liters	14,166,357	38,228	108
Passenger Cars	Gasoline	Liters	3,629,210,490	7,790,911	17,527
Rail					
Commuter Rail	Diesel	Liters	5,064,028	13,789	98
Solid Waste Transport Rail	Diesel	Liters	5,671,501	15,443	552
Subway and Commuter Rail	Electricity	Gigajoules	10,118,346	888,472	7,835

$MgCO_2e$ = One million grams, equal to one metric ton of CO_2 equivalent
* PMT = Passenger-Miles-Traveled, TMT = Ton-Miles-Traveled (freight)

population and employment projections, which were described in Section 3. These were then reapportioned to a new, more efficient and more electrified mix of transportation modes so that the same services are provided as total PMT and TMT stay constant. No credit was taken for lifestyle changes, such as telecommuting or increased videoconferencing. Finally, based on the latest fuel economy standards and other expectations for increased efficiency, we calculated the fuel and electricity consumption, along with the resulting CO_2 emissions. These analyses and results are presented in this section.

TRANSPORTATION EMISSIONS – 2010

The *Inventory* breaks down the different modes used to transport people and goods in New York City by fuel type, as shown in Table 6.1. Out of the total citywide CO_2 emissions, 18 percent are from on-road transportation and only 3 percent are from mass transit. Emissions from passenger cars and trucks, which frequently travel into the city from outside of the city boundaries, are estimated based on when they enter and leave New York City, and commuter rail emissions are estimated based on the portion of the emissions that occur while the trains are within city limits[1].

Using the *Inventory*, we calculated PMT and TMT by applying coefficients for CO_2e per mile traveled. Heavy trucks and solid waste rail are measured in TMT, all other modes are measured in PMT. The coefficients were derived from a variety of sources, including data from the Federal Transit Administration (FTA)[2], the U.S. Department of Transportation (DOT)[3], a report by Transportation Alternatives about the GHG emissions caused by commuting in NYC called "Rolling Carbon,"[4] and other sources[5]. To determine the final coefficients, it was important to account for New York City driving conditions, as the stop-and-go city traffic patterns cause traditional vehicles to run less efficiently than the standard estimates for highway miles per gallon (mpg).

Buses

Bus use in NYC is dominated by MTA's transit bus system. 2.5 million people use this mostly diesel system on an average workday[6]. MTA is currently testing a small fleet of buses powered by compressed natural gas (CNG). This will improve air quality and could have an impact on oil imports, but today, actually produces more GHG emissions per PMT than do the diesel vehicles. CNG busses will certainly do less to reduce carbon emissions than conversions to trolleybuses and hybrids and will therefore not appear in our 2050 transportation modes.

The emissions from nontransit diesel buses include many privately owned in-city and intercity bus companies.

Heavy Trucks

New Yorkers depend on heavy trucks to deliver almost all of the 435 million tons of freight that comes into the city each year[7], and to remove a portion of the solid waste. These trucks contribute to both CO_2 emissions and traffic congestion. As this volume of freight is expected to grow in accordance with our population projections, it will be important to redirect as much freight as possible to more efficient modes of transport, which we have taken to be electrified rail.

Light Trucks

Light trucks include pickup trucks, vans and sport utility vehicles (SUVs), but many of these vehicles are often used as passenger cars. Light trucks are the highest CO_2 emitters per PMT of all transportation modes. Hybrid versions of these vehicles are widely available, but are not yet in a dominant market position.

Passenger Cars

An average car trip in NYC produces significantly more CO_2e than public transportation: roughly twice the amount caused by riding the bus and four times the amount from riding the subway the same distance[8]. Even though NYC has the highest percentage of commuters in the U.S. using nonautomobile transportation, passenger cars are still making a staggering contribution to emissions. In 2010, about 69 percent of transportation emissions came from gasoline-powered passenger cars, including both private cars and taxis.

Figure 6.1: Traffic congestion is a common inconvenience for New Yorkers.

Rail

Rail lines are widely used in NYC to transport both people and freight. Commuter rail lines including Metro-North, New Jersey Transit, and the Long Island Railroad carry passengers into and out of the city from surrounding suburbs in Connecticut, New York and New Jersey. The MTA's subway system currently serves 5.3 million people per day[9] and is the most extensive system in the U.S., with more passengers daily than the combined total of the next five largest U.S. transit systems[10].

As a result of NYC's Solid Waste Transport Plan, which was passed in 2006, 30 percent of the city's waste is now transported out of the city by rail, reducing reliance on heavy trucks[11].

Although the subway and some commuter rail services are electrified, much of passenger rail and all solid waste transport rail are still powered by diesel engines.

Table 6.2: Extrapolation to 2050 Demands

2010 Mode	Fuel Type	2010 PMT/TMT (Millions)	Scaling Type	Scaling Factor	Raw 2050 PMT/TMT (Millions)
Buses					
Transit Buses	Compressed Natural Gas	299	Average	21.5%	363
Transit Buses	Diesel	2,161	Average	21.5%	2,626
Nontransit Buses	Diesel	86	Average	21.5%	105
Heavy Trucks					
Heavy Trucks	Diesel	5,073	Population	14.0%	5,783
Solid Waste Transport Trucks	Diesel	436	Population	14.0%	497
Light Trucks					
Light Trucks	Diesel	214	Population	14.0%	244
Light Trucks	Gasoline	1,696	Population	14.0%	1,933
Passenger Cars					
Passenger Cars	Diesel	108	Population	14.0%	123
Passenger Cars	Gasoline	17,527	Population	14.0%	19,980
Rail					
Commuter Rail	Diesel	98	Employment	29.0%	126
Solid Waste Transport Rail	Diesel	552	Population	14.0%	629
Subway and Commuter Rail	Electricity	7,835	Average	21.5%	9,520

EXTRAPOLATION TO 2050 DEMANDS

After calculating 2010 PMT and TMT, the next step was to scale up the number of miles traveled based on growth predictions for in-city population, for employment (which has a direct effect on commuters), or for an average of the two, as listed in Table 6.2.

Efficiency Measures and Mode Conversions

We then redistributed the scaled-up raw values for 2050 PMT/TMT from 2010 modes to the new 2050 modes. This mode conversion is represented in Table 6.3, which shows what fraction of each PMT and TMT has been redistributed to one new mode or another. PMTs are only distributed into PMTs in new modes, and TMTs into TMTs in new modes. For each 2010 mode, we distributed the PMT/TMTs in ways that were physically plausible, advantageous from an emissions perspective, and otherwise as simple and uniform as possible. So, for example, 10 percent of transit bus PMTs were moved to the subways, 30 percent to electric surface trolleys, and 60 percent remained on buses. We assumed that no PMTs were transferred from buses to passenger cars or light trucks, since this would increase emissions and costs to the passengers. Similar considerations were applied to the other modes.

This broad assumption that both people and freight move to more efficient modes of transportation could be brought about by some combination of increasingly available and attractive rail options, greater congestion, increased fuel prices, incentive programs, and possibly congestion pricing or a carbon tax. We did not consider logistical initiatives to reduce travel emissions, some of which are already underway. UPS, for example, uses sophisticated software to map routes that avoid left turns. In 2010 UPS's routing software eliminated 20.4 million miles from routes nationally and reduced CO_2 emissions by 20,000 metric tons[12]. We also have not taken any credit for lifestyle changes, such as telecommuting and greater workday flexibility to distribute rush hour traffic, although these changes may occur if the growth projected here is realized.

In particular, a percentage of PMT/TMT for every mode of transportation is moved to subways and passenger or freight rail in 2050. As PMT/TMT expands due to population, roads will become more congested, while we assume that at the same time, the subway system will expand, making it a more attractive option relative to on-road options. Also, diesel and gasoline-powered vehicles are converted to turbo diesel, hybrid diesel, and electric vehicles with a relatively uniform distribution.

We did not include fuel cell-powered vehicles as a separate 2050 mode, although they are an attractive long-term option, providing a mechanism to store and utilize hydrogen produced from solar-powered electrolysis. Because they utilize hydrogen directly, this would have required a leap to analyze a complete hydrogen fuel cycle, an effort we could not invest in for one modest portion of the transportation sector. Rather, we assumed that the battery-powered electric vehicles in each sector also represent any fuel cell vehicles.

The PMT/TMT values in the new modes, and the resulting fuel use and emissions, are listed in Table 6.4. The efficiency improvements leading to the lowered fuel consumption and emissions compare 2050 performance to performance in the same mode in 2010, and are discussed in some detail in the following sections.

Buses

The standard diesel transit buses that currently make up the majority of buses in NYC are relatively inefficient and do not appear in the 2050 transportation modes. Some buses remain as diesel-hybrids, but many are converted to electric trolleys.

In the late 1800s and early 1900s, electric trolleys existed in all five NYC boroughs[13]. They declined in the 1920s as bus companies bought the trolley companies and removed the trolleys while the bus system grew quickly.

Modern technology now allows for "trolleybuses" that have rubber tires like traditional buses, but are powered by overhead electric wires and can move more freely with traffic[14]. New battery technology also makes it possible for trolleys to temporarily disconnect from wires, and eliminates the need for unreliable and unsightly crossed wires in intersections. This technology is already being put to use in San Francisco and other cities around the world and could greatly reduce CO_2 emissions from current bus travel in NYC.

Table 6.3: Conversion of 2010 Passenger-Miles-Traveled and Ton-Miles-Traveled to 2050 Modes

2010 Mode		Fuel	Transit Buses - Trolleys	Transit Buses (Hybrid)	Nontransit Buses	Heavy Trucks	Solid Waste Transport Trucks	Light Trucks / SUVs (Turbo)	Light Trucks / SUVs (Hybrid)	Light Trucks / SUVs	Passenger Cars (Turbo)	Passenger Cars (Hybrid)	Passenger Cars	Freight Rail	Soild Waste Transport Rail	Subway and Commuter Rail
		Fuel	Electricity	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Electricity	Diesel	Diesel	Electricity	Electricity	Electricity	Electricity
Buses	Transit Buses	CNG	30%	60%												10%
	Transit Buses	Diesel	30%	60%												10%
	Nontransit Buses	Diesel			50%											50%
Heavy Trucks	Heavy Trucks	Diesel				90%								10%		
	Solid Waste Transport Trucks	Diesel					80%								20%	
Light Trucks	Light Trucks/ SUVs	Diesel and Gasoline						20%	20%	10%	10%	10%	10%			20%
Passenger Cars	Passenger Cars	Diesel and Gasoline	5%	5%							25%	25%	20%			20%
Rail	Commuter Rail	Diesel														100%
	Solid Waste Transport Rail	Diesel													100%	
	Subway and Commuter Rail	Electricity														100%

Table 6.4: 2050 Emissions and Electricity Use

2050 Mode	Fuel Type	Fuel Unit	2050 PMT/TMT (Millions) in 2050 Modes	Efficiency Increase from 2010*	Fuel Consumed (Thousands)	Emissions $MgCO_2e$
Buses						
Transit Buses - Trolleys	Electricity	Gigajoules	1,902	15%	2,136,000	0
Transit Buses (Hybrid)	Diesel	Liters	2,799	10%	179,465,000	484,700
Nontransit Buses	Diesel	Liters	53	10%	4,170,000	11,261
Heavy Trucks						
Heavy Trucks	Diesel	Liters	5,205	30%	257,683,000	695,949
Solid Waste Transport Trucks	Diesel	Liters	398	30%	19,688,000	53,175
Light Trucks						
Light Trucks / SUVs (Turbo)	Diesel	Liters	435	124%	33,606,000	90,685
Light Trucks / SUVs (Hybrid)	Diesel	Liters	435	171%	27,495,000	74,197
Light Trucks / SUVs	Electricity	Gigajoules	218	20%	240,000	0
Passenger Cars						
Passenger Cars (Turbo)	Diesel	Liters	5,244	246%	317,355,000	856,385
Passenger Cars (Hybrid)	Diesel	Liters	5,244	318%	259,654,000	700,678
Passenger Cars	Electricity	Gigajoules	4,238	20%	3,662,000	0
Rail						
Freight Rail	Electricity	Gigajoules	578	20%	51,000	0
Solid Waste Transport Rail	Electricity	Gigajoules	728	20%	64,000	0
Subway and Commuter Rail	Electricity	Gigajoules	14,453	15%	16,231,000	0

* These are efficiency improvements in the various transport modes assumed achieved by 2050, when compared with the same technology in 2010.

We assumed that new batteries and controls will allow trolleybuses to operate on 15 percent less electricity in 2050 than they do now, and that standard diesel buses are 10 percent more fuel efficient, due to modest incremental improvements.

Truck Transport

Since it is currently very difficult for electric vehicles to move heavy loads of goods and waste, we retained a substantial amount of the diesel truck fleet, while shifting about 10 percent of the freight to electric rail. The feasibility of the electric rail will depend in large part on the construction of a freight tunnel under New York Harbor, from New Jersey into Brooklyn. This project, known as the Cross-Harbor Rail Tunnel, has been proposed many times, but has failed to materialize. It is included here because it provides real value both for relieving stress on roads and for allowing conversion to electric power.

The 30 percent increase in fuel efficiency is the smallest improvement anticipated by industry experts, and results from improved motor controls, transmissions, and maintenance. Although hybrid trucks are becoming available[15] and would seem appropriate to city driving patterns, we did not feel confident predicting a level of market penetration for them, and have not included this technology in our projections. They do, however, serve as a backstop justification for the overall 30 percent improvement.

Light Trucks and SUVs

To reduce the carbon emissions from light trucks, this study relies on purchasing decisions (consumers choosing to buy passenger cars over SUVs) and a rise in the availability of more efficient turbo-diesel, diesel-hybrid and electric SUVs, instead of on large-scale infrastructure improvements. The efficiency improvements for the diesel-powered vehicles are simply the recently promulgated Corporate Average Fuel Economy (CAFÉ) standards, now required by 2025[16], and assumed to be fully implemented by 2050.

Figure 6.2: (a) Electric trolleys in Union Square, New York, circa 1906 (b) A trackless trolley, one of four trolleybus routes from the Massachusetts Bay Transportation Authority in Boston

Passenger Cars

Passenger cars currently have the biggest impact on transportation emissions. In 2050, 30 percent of PMT is shifted to transit options including passenger rail. The increase in passenger rail would require some rail to be diverted to the Access to the Region's Core (ARC) tunnel, also known as the Hudson River Tunnel, proposed to run from Secaucus, N.J., to midtown Manhattan, increasing the capacity of New Jersey Transit substantially. This tunnel project was canceled in 2010 due to budgetary concerns; however, this is a much more likely option in the near future than the freight tunnel, and will reduce pressure on many other modes of transport.

As for light trucks, the remaining passenger cars are converted to turbo-diesel, diesel-hybrid and full electric, and efficiency is again increased in accordance with the 2025 CAFÉ standards. Due to higher compression, diesel engines are generally capable of higher efficiency than gasoline-powered engines. For hybrids and full electric cars, regenerative braking is very effective in the stop-and-go city driving. In 2011, Paris launched an electric auto-share program[17], proving that electric cars can be practical in cities.

Rail

As mentioned earlier, freight rail would be expanded with the Cross-Harbor Rail Tunnel and we assumed that all freight trains, including those for waste removal, will be electric.

Subway and passenger rail is expanded and converted to all-electric in 2050, picking up many passengers from other modes. We anticipate continued increases in subway ridership, so much so that it is clear the new ridership cannot fit on the existing subway. The Lexington Avenue line (the 4 and 5 express trains) physically cannot add any more trains to the track during rush hour. So we are counting on a rapidly expedited Second Avenue subway extending all the way to Hanover Square downtown, as well as continued expansion of other lines, such as the extension of the 7 line to the Javits Center and the extension of the AirTrain into Manhattan.

We incorporated a 15 percent improvement in subway efficiency, which the MTA is already planning as their "medium case" energy-reduction goal just by utilizing existing light weighting technology and regeneration[18].

Table 6.5: Summary Comparison and Savings for Transportation

Year	PMT (Millions)	TMT (Millions)	Electricity Use (GJ)	Electricity Use (GWh)	Fuel Use (Million Liters)	Emissions $MgCO_2e$
2010	30,000	6,061	10,118,000	2,811	4,331	11,355,000
2050	35,000	6,909	22,380,000	6,218	1,099	2,967,000
2010 Fuel Use is measured in diesel equivalent; 2050 Fuel Use is all diesel						

Figure 6.3: Autolib', an electric car-share program in Paris, demonstrates that electric cars can work in cities.

FINAL TRANSPORTATION SECTOR EMISSION ESTIMATES

The overall results for transportation are summarized in Table 6.5, and show that an achievable increase in electric energy can lead to substantial savings in fuel use and emissions. The current transportation system is already very effective and dramatically reduces the carbon footprint of living and working in New York, but it is clear that the changes discussed here could dramatically improve the system- making it more convenient, safer and efficient than today. Given our projection of zero energy buildings, these infrastructure advancements will make it possible to meet and exceed the overall citywide goal of a 90 percent reduction. Additional reductions, or a cushion against problems with the methods outlined here, can be achieved through steps we have not included, such as further increases in bicycle use and expanded ferry services.

7. WASTE AND OTHER SECTORS

INTRODUCTION

A small portion of NYC's greenhouse gas (GHG) emission profile results from landfills, the processing of wastewater, fugitive emissions (unintended leaks) from exported solid waste, vehicle refrigerant systems, and the distribution of natural gas and electricity. The emission totals in each category for 2010 are simply matched to the Inventory. For 2050, population growth is used to estimate certain emission trends, particularly those concerning wastewater and solid waste, and various reduction technologies or programs are implemented to cut waste and in some cases, generate additional power.

EXPORTED SOLID WASTE AND LANDFILLS

The NYS Department of Environmental Protection's plan, *Beyond Waste: A Sustainable Material Management Strategy,* sets out a 20-year goal of reducing the average amount of waste that New Yorkers dispose of from 4.1 to 0.6 pounds per person, per day[1]. A more conservative, but still aggressive reduction plan was declared by plaNYC, which hopes to divert 75 percent of the city's solid waste from landfills by 2030. This plan will require substantial behavioral changes in the community at large, so we almost double the amount of time needed to meet this goal and assume that the 75 percent reduction can be fully achieved by 2050.

The NYC population is expected to grow 14 percent from 2010 to 2050, with a corresponding relative increase in the amount of waste produced. If methane capture techniques above the landfill waste and exported solid waste are capable of collecting just half of the methane produced by decomposers, and the 75 percent reduction achieved, the amount of methane released to the atmosphere can be reduced by 86 percent from 2010 levels. Additionally, the gas can be collected and burned for electricity generation. Assuming a 30 percent conversion efficiency from gas turbines, it would be possible to produce just over 40 GWh of electricity annually, and we have taken this as a portion of the needed carbon-free electricity.

SOLID WASTE TO STEAM

Citywide consumption from Con Edison's district steam system in 2010 was about 23 billion pounds of steam[2]. Including Con Ed-reported line losses and assuming a conservative plant-level thermal efficiency of 65 percent, about 39 trillion Btu are needed annually as input into the steam system at 2010 usage levels.

Figure 7.1: Fresh Kills Landfill in Staten Island, 1973. The site was closed in 2001.

Figure 7.2: Methane capture vent at Freshkills Park, a landfill reclamation project in Staten Island.

Coincidentally, about 39 trillion Btu would be available from the waste-to-energy (WTE) conversion of the dry portion of the NYC solid waste stream, which was about 2.2 million tons in 2010[3]. Therefore, WTE plants using just the dry portion of the current waste stream could roughly power the current steam system. This includes combusting recyclable paper, plastic, and wood in the waste stream.

However, assuming steam is kept as an input to only the buildings presently using it, and assuming the energy-use intensity (EUI) improvements shown by the model, 2050 steam consumption would be only about 1/6 of the 2010 use, or 6.5 million MMBTU. Thus, available thermal energy from the current dry solid waste stream is six times larger than projected 2050 thermal needs in the steam system. Even if the planned 75 percent reduction in landfill volume is achieved in the dry portion of the waste stream, there would still be enough fuel to maintain the greatly reduced system steam load.

Additionally, potential biogas production from the wet portion of the 2010 waste stream is approximately 2.2 million MMBTU[4]. This resource could provide one-third of the projected 2050 steam system thermal consumption, further cutting WTE needs.

However, the steam system is now more than 100 years old and is in famously poor repair, so it is far from clear how much of it will be usable in 40 years. Also, siting trash-combustion equipment within city limits is currently politically onerous, although biodigestion may prove viable. For these reasons, we have not included this option in our totals.

NATURAL GAS DISTRIBUTION

Emissions from the natural gas distribution system are the consequence of leaky, unprotected piping and faulty connections. In the "90 by 50" future, natural gas will no longer be utilized as a fuel for buildings, and electric generation will rely on renewable sources, so there will be no need for a natural gas distribution system. We therefore expect no fugitive emissions in this category in 2050.

WASTEWATER TREATMENT

Wastewater treatment plants (WWTPs) are responsible for emissions of numerous greenhouse gases, with substantial amounts of methane and nitrous oxide, or N_2O. As an engineering rule of thumb, a typical WWTP processes 100 gallons per day of wastewater for each person served[5]. Additionally, for each million gallons per day processed by anaerobic digesters, the available biogas, composed of mostly methane and some N_2O, can generate roughly 26 kW of electric capacity[6]. With the combination of residential population and the daily surge of commuters, NYC's 14 WWTPs located throughout the five boroughs currently treat 1.3 billion gallons of wastewater daily. As the NYC population is expected to reach 9.35 million by 2050, the WWTPs will be responsible for processing more than 1.4 billion gallons of wastewater per day. Even if water conservation measures lead to lower flow rates, the amount of biological material will remain tied to the population, and that is the source of the biogas. With proper biogas capture, this can lead to the generation of 36 MW of electric capacity.

MUNICIPAL VEHICLE FLEET

The New York City Department of Citywide Administrative Services tracks the fugitive emissions of hydrofluorocarbons (HFCs) from municipal vehicle cooling and refrigeration systems. HFCs have recently been implemented as a superior class of refrigerants after the phasing out of such ozone-depleting refrigerants as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)[7]. These chlorine-containing refrigerants released chlorine radicals into the atmosphere, which reacted with ozone molecules and allowed additional ultraviolet radiation to penetrate the Earth's surface[8]. Although the currently used HFCs do not lead to ozone depletion, they do have very substantial global warming potentials[9].

Leaks from these systems amount to a small portion of the city's GHG emissions profile, but a greater effort is needed to increase monitoring and frequent testing of equipment. For 2050 emissions, we have assumed that a combination of better leak control and improved refrigerants with lower global warming potentials will make possible a 75 percent decrease in these emissions.

ELECTRICITY DISTRIBUTION

Sulfur hexafluoride, or SF_6, is widely used in electrical transmission and distribution systems, as well as in circuit breakers and magnesium production. With a global warming potential of 23,900[10], gas leaks, even in small amounts, can have a substantial impact on greenhouse gas emissions.

The Electric Power Research Institute (EPRI) has performed much experimental research in the search for a possible replacement. However, no single gas was found to be an acceptable substitute for SF_6. EPRI has turned its focus to developing a camera that allows the visualization of SF_6 leak sites with a video detection system. The camera provides real-time images that are sensitive to leaks as small as 2 pounds per year and viewed at distances as far as 100 feet[11]. By implementing process improvements and emission-control techniques, we assume that emissions due to SF_6 leaks can be reduced by 75 percent by 2050.

STREETLIGHTS AND TRAFFIC SIGNALS

In a carbon-free electric economy, the electricity used for streetlights and traffic signals will not be associated with any GHG emissions. Most traffic signals have already been equipped with LEDs, and tests and demonstrations are underway with LED streetlamps. Additional studies may explore efficiency upgrades for the lighting technologies, but such improvements were not considered at this time.

FINAL EMISSION ESTIMATES FOR WASTE AND OTHER SECTORS

Table 7.1 shows our estimates of the emission reductions and associated biogas electricity generation as they contribute to our overall totals. Altogether, the electricity generated corresponds approximately to the output of a 41 MW generator running continuously. While not a great deal of power, it may also be possible to use the thermal energy to promote digestion processes.

Table 7.1: Waste and Other Sectors - Emissions, Reductions and Electricity Generation

Source	Fuel	2010 Emissions (Million Metric Tons CO_2e)	2050 Emissions (Million Metric Tons CO_2e)	Reduction	2050 Electric Generation (GWh)
Exported Solid Waste	CH_4	1.28	0.18	86%	38.7
Landfills	CH_4	0.10	0.014	86%	3.0
Natural Gas Distribution	CH_4	0.34	0	100%	N/A
Wastewater Treatment Plants	CH_4	0.20	0	100%	315
Municipal Vehicle Fleet	HFCs	0.01	0.0025	75%	N/A
Wastewater Treatment Process	N_2O	0.09	0	100%	N/A
Electricity Distribution	SF_6	0.26	0.065	75%	N/A
Streetlights and Traffic Signals	Electricity	0.08	0	100%	N/A
Total		**2.35**	**0.26**	**89%**	**360**

8. ENERGY AND EMISSION REDUCTION ESTIMATES

EMISSIONS REDUCTIONS

The only emissions considered in 2050 will be those in the transport and fugitive and process sectors. We have already seen in Sections 6 and 7 that these can be reduced to less than 10 percent of 2010 emissions, and the results are summarized in the right column of Table 8.1.

DEMAND FOR CARBON-FREE ELECTRIC ENERGY

Eliminating the use of fuels has led to a need for substantial amounts of electric energy, which we assume will be produced by carbon-free sources. In this section we review the sectoral electricity demands and briefly discuss the options for obtaining carbon-free electric energy.

ELECTRIC ENERGY NEEDED FOR BUILDINGS

The electric energy and demand needed to power the buildings is summed across building sectors. The total requirements to maintain the city's buildings for one year were 50.6 TWh, about equal to today's total consumption. This is gross energy needed by buildings, independent of production from photovoltaic (PV) panels on roofs. We found that on-site PV production could produce 10.7 TWh, reducing net electric energy use (including other sectors) to 46 TWh.

In our second, less rigorous scenario, infiltration was allowed to double to 0.4 air changes per hour, and insulation R-values were lowered by about 30 percent, to R-15 on residential walls, for example. As a result, the electric energy needed for buildings increased by about 6 percent to 53.7 TWh. This modest increase implies that we may be able to tolerate a less rigorous program of building improvement than has been modeled here, but substantial analysis will be needed to clarify the cost of different levels of retrofit.

TRANSPORTATION ELECTRIC ENERGY

The results for the transportation sector are shown in context in Table 8.1, and electric energy constitutes about 23 percent of transportation's total energy. Some of this is energy to charge batteries in all-electric vehicles, which will have a leveling effect on the grid, but we have not been able to quantify this benefit.

Table 8.1: 2050 Fuel and Emission Totals by Sector

Sector	Electricity Use (GWh)	Electricity Generation (GWh)	Net Electricity Use (TJ)	Net Electricity Use (GWh)	Diesel Fuel Use (Million Liters)	GHG Emissions (Million $MgCO_2e$)
Buildings	50,600	10,700	143,600	39,900	0	0.00
Transportation	6,200	0	22,300	6,200	1,100	2.97
Fugitive and Process	0	360	-1,300	-360	0	0.26
Streetlights and Signals	240	0	860	240	0	0.00
Total	**57,000**	**11,000**	**165,000**	**46,000**	**1,100**	**3.23**

Figure 8.1: Offshore Wind Farm

WASTE AND OTHER ELECTRIC ENERGY

Table 8.1 makes it clear that waste is actually a modest net benefit with respect to electric energy, producing energy one would expect from a 41 MW generator running at all times. The bulk of this energy comes from solid waste decomposition, which would most likely take place outside of the city, but since the waste originated here, it is counted in this tally. Sewage treatment plants provide substantially less power than solid waste, due to the much smaller amount of biomass in the stream.

Although we took no direct credit for it, due to problems discussed in Section 7, the city's solid waste could also be used to supply heat that would permit the Con Edison steam system to continue operation, especially at reduced levels commensurate with the reductions in building load discussed above.

TOTAL ELECTRIC ENERGY

In sum, our modeling of a future involving deep but entirely practical retrofits of buildings and mode switching and efficiency improvements in transportation shows that New York City can get by on slightly more electric energy than it is using now, about 57 TWh gross and 46 TWh net of PV production on buildings.

Under the less rigorous scenario with higher infiltration, gross electric energy needed would rise to 60 TWh, and the net to about 49 TWh.

POTENTIAL SOURCES OF CARBON-FREE ELECTRIC ENERGY

We have indicated that about 57 TWh of carbon-free power are needed, of which rooftop photovoltaic panels will supply 11 TWh. A serious study of sources for the remaining power is beyond our scope, and, on a larger scale, at least two such studies have already been carried out[1,2]. Instead, we list several options with brief comments.

- Maintain the roughly 19 TWh of carbon-free power the Inventory reports is currently used by New York City. That will leave 27 TWh, all of which can be supplied by:
    - 2600 4.0 MW wind turbines, occupying 35 to 40 square miles, either upstate or off shore, or
    - 86 million square meters of photovoltaic panels with a footprint of 66 square miles, much of which could be on the parking lots, rail yards, and highways included in New York City's 350 square miles, or
    - 3 or 4 new 1000 MW nuclear power plants (if cost, siting, and waste issues can be resolved), or
    - Increased hydropower from Quebec (transmission lines are under construction now), or
    - Any combination of the above.
- Also:
    - Tidal power is proving itself but remains a development project with modest local potential.
    - Solid waste combustion may be able to supply the steam system, cutting electric loads.

- However:
  - » Distant (for instance, upstate) PV farms are less effective than on-site and near-site modules, due to the poor solar resource in the northeast, and
  - » Local, on-building wind turbines perform poorly due to the limited local resource and are usually rejected as neighbors over noise and visual concerns.

This brief survey indicates that supplying carbon-free electric energy to New York City in 2050 is plausible. Far more detailed study is clearly needed.

PEAK LOADS AND IMPACT ON GRID

Our estimates of demand on the electrical grid due to buildings followed from our models. eQUEST calculates the peak electric demand in kilowatts for each building. Deriving an estimate of total peak demand on the electric distribution system was complicated by the fact that all buildings do not peak at the same time, but their peaks, being driven by similar loads, are somewhat coherent. To derive the peak load imposed on the system, we used a diversity factor of 23.1 percent, meaning a 76.1 percent reduction below the simple sum of individual building demands. This diversity factor was derived from our 2010 models, by finding a value that would equate the scaled sum of the 2010 building demands to the building peak load of 7,960 MW in 2010 reported by Con Edison[3]. It is risky to apply a diversity factor derived from a summer, daytime, air conditioning peak to a winter, nighttime, space heat driven peak, but it is the only available way to connect our models to Con Edison's citywide data. Doing so gave a peak 2050 building load of 12,600 MW by 2050, a 58 percent increase. This would correspond to a substantial decrease in the system load factor, from 73 percent to 46 percent. This result is not surprising, since heat pumps generate a peaked load like air conditioners, but based on heating loads. The increased peaks will provide strong motivation to implement thermal storage and other load leveling technologies, but we have not evaluated them in this study.

Electric demand for transport will be substantial, but we do not have the resources to calculate it. Average transport power (annual energy divided by the length of a year) is about 850 MW, but peak demand is likely to be two to three times that. Transportation demand will be ameliorated somewhat by the leveling effect of charging electric car batteries when solar electricity is available in the daytime.

These results indicate that while the "90 by 50" program will call for ongoing upgrades to the electrical distribution system, the changes can be planned for and are technically feasible.

APPENDIX A: SCALING THE 2010 MODELS TO THE CITY

Section 2 described the creation of a model of energy use in New York City's buildings. This appendix contains more detail on how the models were tuned to agree with the *Inventory's* data.

BUILDING ENERGY USE

Each building type may have its heat and hot water needs served by more than one fuel, including gas, oil (#2, #4, and #6), electricity and Con Ed steam. Rather than create separate eQUEST models for each heating system, we modeled the buildings as if electric resistance heaters provided the thermal energy. The energy consumed by the heaters represents the heating and hot water loads for that building.

Then we calculated fuel use for each type of heat used in each building. (See Table 2.3.) In some cases we had specific knowledge of which buildings used which fuels, such as all modern high rise commercial buildings using only gas. In other cases, several different fuels are used in a given building type, and only broadly qualitative data is available on these fuel shares. Since the *Inventory* provides good data on total fuel use, it was possible to allocate shares of each building model across fuel types as part of the scaling process, which was designed so that both fuel use and carbon emissions match the *Inventory* data exactly.

Matching building fuel use and emissions to those in the *Inventory* was also achieved by making adjustments to building characteristics such as infiltration, insulation, and the efficiency of the different fuel-using equipment.

In addition to fuel use, electric energy use within the buildings is modeled in some detail by eQUEST, and affects both heating and cooling loads. Rather than rely on eQUEST defaults, we looked to outside sources of data on cooking, plug loads, electronics, pumps and fans, and all the other uses of electricity in a building, as well as gas used for cooking and drying laundry. A standard source for this data is the Buildings Energy Data Book (BEDB)[1], but we found it difficult to reconcile the data therein with New York City's benchmarking data and other local sources, perhaps because the BEDB is national in scope. Similarly, we found it difficult to reconcile our data with Residential Energy Consumption Survey (RECS)[2] and Commercial Building Energy Consumption Survey (CBECS)[3] data, which are, again, national in scope.

Usage data much more consistent with local sources was obtained from a detailed study carried out for Con Edison in 2011[4]. Although the Con Ed energy use categories did not quite match those used in eQUEST, they were close enough to develop reasonable values for internal energy use in the eQUEST categories. Finally, the most recent data available on New York City energy use comes from the city's benchmarking data[5], and we found that by scaling the Con Edison data up by 11 percent for residential buildings, and down by 13 percent for commercial buildings, we could produce a set of internal energy use intensities (EUIs) that were roughly consistent with the Con Edison results while matching the overall EUIs from the benchmarking data. The Con Edison data was used without this scaling for the one or two family house, since the benchmarking data does not apply there[†]. The resulting internal loads are summarized in Table A.1. The upper group of internal loads was used as fixed inputs to eQUEST. The heating and cooling loads at the bottom of Table A.1 were used as targets, and eQUEST energy use was matched to them by adjusting insulation levels and infiltration, while ensuring that these quantities remained in reasonable physical ranges. In the end, energy use found by eQUEST matched the benchmarking EUI for each building type.

Table 2.3 includes a column indicating the source EUI we found for each building model. The source EUI of a building includes both the energy consumed within the building (known as "site EUI") and an allowance for the energy used outside the building in the production of the energy used inside the building. By far the largest out-of-building element is the fuel used in power stations to generate electric energy, which is roughly triple the energy delivered as electricity. The U.S. Environmental Protection Agency (EPA) maintains a website, Portfolio Manager, where building energy use data can be entered and compared to other buildings, and the New York City benchmarking data is entered using Portfolio Manager. The EPA defines the source energy to site energy ratio for electricity to be 3.34, representing national average power plant performance. (That is, it takes 11,400 Btu of fuel to produce 1.0 kWh of electric energy.) Because NYC benchmarking uses Portfolio Manager, all its analysis is carried out using this national average ratio of 3.34.

However, this ratio is not appropriate to our analysis for two reasons. First, even in 2010, New York City used a much cleaner mix of generation sources than the national average, and the *Inventory* (App. H) finds the New York City ratio to be 2.867, a heat rate of 9782 Btu/kWh. We used this rate in calculating source EUIs in 2010 for Table 2.3. In that way our EUIs represent New York City's fuel use and emissions accurately, which would not be the case if we used the national average. When we compared our results to those from benchmarking, we used the EPA's national average figure, since that is how those source EUIs were computed.

† Although technically the row house and low rise residential are too small to be included in benchmarking (having less than 50,000 square feet), the apartments are sufficiently similar to those in larger buildings to warrant scaling to benchmarking EUIs for them as well.

Table A.1: 2010 Internal Building Loads

Type	Unit	1-2 Family House	Other Residential	Commercial
Used as Inputs in eQUEST:				
Ambient Lights	kWh/sf	0.890	0.988	3.428
Miscellaneous Equipment	kWh/sf	2.650	2.942	6.872
Pumps & Aux. Equipment	kWh/sf	0.416	0.107	0.260
Vent Fans	kWh/sf	0.080	0.089	2.034
Domestic Hot Water*	kWh/sf	3.250	3.608	1.121
Exterior Usage	kWh/sf	0.190	0.211	0.764
Stoves & Dryers (Gas Appliances)	Gas Btu/sf	6,500	7,215	5,395
Used as Targets in eQUEST:				
Space Heating*	kWh/sf	11.500	12.765	9.960
Space Cooling	kWh/sf	0.600	0.666	2.490

* Heating and Domestic Hot Water loads are depicted as electric at 100% efficiency; fuel efficiency is treated elsewhere

APPENDIX B: COST TABLES

The two tables on the following page present the detailed breakdown of unit and building-wide costs. Table B.1 gives detailed information on unit costs (costs per square foot), which refer, as noted, either to floor area or to the area being reconstructed. Table B.2 presents the total costs for implementing all applicable measures in each of our prototype buildings, and it is these costs that are scaled up to derive costs for the entire project, as described in Section 5.

Table B.1: Individual Measure Unit Cost Estimates by Building

Building Type (Estimates by floor area, opaque wall area or glazed area as indicated)	Cost Category / Area Used	Envelope					Space Heat/Cool			Domestic Hot Water		
		Air-seal Units (Res) or Building (Com) to 0.1 ACH	During Re-skinning, Lower Vision Glass to 50% Max.	Insulate Opaque Areas (Res: R-50 Roof, R-20 Walls; Com: R-30 All Exposed Surfaces)	Triple Glaze All Fenestration with U ≤ 0.20 Polymer Film Triple Glazing	Add 3' Sunshades to South Windows	Energy Recovery Ventilation	Mini-split Heat Pumps	Ground Source Heat Pumps, Hydronic H&C Distribution	DHW Loop on GSHP	DHW HP Operating in Conditioned Space	Heat Recovery for DHW on ACs
		Floor Area	Floor Area	Opaque Area	Glazed Area	Floor Area	Floor Area	Floor Area	Floor Area	Floor Area	Floor Area	Floor Area
1 or 2 Family House	Standard Replacement: High-Performance Item: Increment:	$ 6.00		$ 2.60	$ 35.00 $ 50.00 $ 15.00	$ 1.50	$ 1.50	$ 3.85 $ 2.60 $ (1.25)			$ 2.00	$ 1.00
Row House	Standard Replacement High-Performance Item:: Increment:	$ 6.00		$ 2.60	$ 35.00 $ 50.00 $ 15.00	$ 1.50	$ 1.50	$ 3.85 $ 2.60 $ (1.25)			$ 2.00	$ 1.00
Low Rise Residential	Standard Replacement: High-Performance Item: Increment:	$ 6.00		$ 2.60	$ 35.00 $ 50.00 $ 15.00	$ 1.50	$ 2.99	$ 3.85 $ 2.60 $ (1.25)			$ 2.00	$ 1.25
Masonry High Rise Residential	Standard Replacement: High-Performance Item: Increment:	$ 3.60		$ 2.60	$ 65.00 $ 90.00 $ 25.00	$ 2.05	$ 2.99		$ 4.00 $ 22.00 $ 18.00	$ 2.00		$ 0.10
Window Wall High Rise Residential	Standard Replacement: High-Performance Item: Increment:	$ 2.30		$ 2.60	$ 75.00 $ 100.00 $ 25.00	$ 3.00	$ 2.99	$ 8.00 $ 3.60 $ (4.40)			$ 2.00	$ 0.10
Low Rise Commercial	Standard Replacement: High-Performance Item: Increment:	$ 16.03		$ 2.60	$ 65.00 $ 90.00 $ 25.00	$ 2.75	$ 4.07		$ 11.00 $ 30.00 $ 19.00	$ 2.08		$ 1.85
Masonry High Rise Commercial	Standard Replacement: High-Performance Item: Increment:	$ 2.28		$ 2.60	$ 65.00 $ 90.00 $ 25.00	$ 3.25	$ 5.99		$ 12.00 $ 26.00 $ 14.00	$ 1.80		$ 0.11
Curtain Wall High Rise Commercial	Standard Replacement: High-Performance Item: Increment:	$ 2.31	$ 5.00	$ 1.50	$ 120.00 $ 150.00 $ 30.00	$ 4.00	$ 5.99		$ 12.00 $ 28.00 $ 16.00	$ 1.80		$ 0.11

Table B.2: Detailed Cost Tables

Building Type	Cost Category	Envelope					Space Heat/Cool			Domestic Hot Water			Total Incremental Cost	Incremental Cost per Unit or per Square Foot
		Air-seal Apartments or Building	Lower Vision Glass to 50% Max.	Insulate Opaque Areas	Triple Glaze All Fenestration	Add 3' Sunshades to South Windows	Energy Recovery Ventilation	Mini-split Heat Pumps	Ground Source Heat Pumps, Hydronic Distribution	DHW Loop on GSHP	DHW Air Source HP	Heat Recovery for DHW on ACs		
1 or 2 Family House	Standard: Proposed: Increment:	$ 8,112		$ 6,548	$ 11,739 $ 16,771 $ 5,031	$ 2,028	$ 2,028	$ 5,205 $ 3,515 $ (1,690)			$ 2,704	$ 1,352	$ 26,114	$ 26,114
Row House	Standard: Proposed: Increment:	$ 11,954		$ 4,183	$ 14,172 $ 20,246 $ 6,074	$ 2,988	$ 2,988	$ 7,670 $ 5,180 $ (2,490)			$ 3,985	$ 1,992	$ 31,674	$ 15,837
Low Rise Residential	Standard: Proposed: Increment:	$ 51,350		$ 24,913	$ 111,636 $ 159,480 $ 47,844	$ 12,838	$ 25,590	$ 32,950 $ 22,252 $ (10,698)			$ 17,117	$ 10,698	$ 179,652	$ 12,832
Masonry High Rise Residential	Standard: Proposed: Increment:	$ 442,699		$ 193,968	$ 1,849,849 $ 2,561,329 $ 711,480	$ 252,092	$ 367,686		$ 491,888 $ 2,705,382 $ 2,213,494	$ 245,944		$ 12,297	$ 4,439,661	$ 21,657
Window Wall High Rise Residential	Standard: Proposed: Increment:	$ 425,023		$ 229,778	$ 6,095,143 $ 8,126,857 $ 2,031,714	$ 554,378	$ 552,530	$ 1,478,342 $ 665,254 $ (813,088)			$ 612,203	$ 612,203	$ 4,204,742	$ 15,631
Low Rise Commercial	Standard: Proposed: Increment:	$ 243,178		$ 36,096	$ 175,443 $ 242,920 $ 67,478	$ 41,718	$ 61,743		$ 166,872 $ 455,105 $ 288,233	$ 31,554		$ 28,065	$ 554,886	$ 36.58
Masonry High Rise Commercial	Standard: Proposed: Increment:	$ 522,688		$ 263,497	$ 2,447,520 $ 3,388,874 $ 941,354	$ 745,059	$ 1,373,202		$ 2,750,988 $ 5,960,475 $ 3,209,486	$ 412,648		$ 25,217	$ 6,970,464	$ 30.41
Curtain Wall High Rise Commercial	Standard: Proposed: Increment:	$ 445,386	$ 964,039	$ 108,405	$ 18,926,619 $ 23,658,273 $ 4,731,655	$ 771,232	$ 1,154,919		$ 2,313,695 $ 5,398,621 $ 3,084,926	$ 347,054		$ 21,209	$ 11,183,439	$ 58.00

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