Energy for Sustainable Development 23 (2014) 46–58

Contents lists available at ScienceDirect

Energy for Sustainable Development

New York City can eliminate the carbon footprint of its buildings by 2050

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ARTICLE INFO

Article history:
Received 11 March 2014
Revised 23 June 2014
Accepted 25 June 2014
Available online xxxx

Keywords:
Climate change mitigation
Energy modeling
Scenario analysis

ABSTRACT

Climate scientists agree that a drastic reduction in carbon emissions in the coming decades is necessary to avoid major disasters due to global warming. Using computer modeling, citywide data sets, and insights from experts in the building community, we show how New York City (NYC) can lead the way toward climate change mitigation by improving the efficiency of its building sector (which is currently responsible for 75% of its greenhouse gas emissions) by 2050 using technologies available today. Though the total elimination of greenhouse gas emissions is possible only with the use of carbon-free energy sources, emissions can be reduced by over 60% from energy efficiency measures alone. After eliminating fuel combustion, carbon-free electric energy roughly equal to total electric energy used in 2010 would be consumed, but with a peak demand 60% higher than today's, establishing requirements for generation capacity and storage. Our economic analysis of the building measures shows them to be essentially cost-neutral over time.

Introduction

Nearly all climate scientists (Allen et al., 2009; Hansen et al., 2013; Meinshausen et al., 2009) tell us that to avoid catastrophic global warming we must dramatically reduce carbon emissions in the global economy by 2050. For developed countries, emissions must be at least 80% below current (2005–2010) levels by 2050 to limit the atmospheric carbon dioxide (CO_2) concentration to less than 450 ppm, which could maintain global temperature increases of less than 2 °C (IPCC, 2013; Union of Concerned Scientists, 2007).

A key component of realizing this reduction is the radical reduction of carbon emissions from the built environment. We show that when deep efficiency improvements are combined with carbon-free electric energy, complete elimination of these emissions is possible. In determining the feasibility of this goal, we have focused on what is possible in the building sector with presently available technology. We refer to reduction "measures" rather than "proposals" to indicate that we do not recommend any specific steps. Rather, we construct one illustrative scenario to demonstrate feasibility. An actual future reaching our targets will employ a much wider range of specific reduction measures. Also, the buildings we examine are taken as average in performance. In reality, some buildings will not be able to meet our goals, but others, especially in new construction, will exceed these goals substantially.

We did not examine year-by-year developments over the coming decades. Instead, we examined the city as a whole, and looked in detail only at the two endpoints, 2010 and 2050. We believe this allows us to sketch a credible future that meets the reduction goal. However, significant development of trajectories will be required to serve as a basis for specific policy proposals (City of New York, 2013).

Material and methods

Building sector emissions in 2010

We created computer models for eight buildings representative of NYC's building stock, scaled their energy use and emissions to reflect citywide data, and tuned the models to match actual consumption and emissions in 2010.

Approach

Since 2007, NYC has maintained a detailed accounting of greenhouse gas (GHG) emissions as part of plaNYC (City of New York, 2011). In this work we used the September 2011 release of the "Inventory of NYC Greenhouse Gas Emissions" (Inventory) to provide a detailed picture of emissions in 2010, which we used as our base year. Our study was restricted to Scope 1 and Scope 2 emissions (California Air Resources Board, 2010) as reported in the Inventory. Scope 1 covers direct emissions, such as from boilers and cars, and Scope 2 covers emissions due to energy consumed in the city but generated elsewhere, such as electricity. Scope 3, which we omitted, includes items such as the emissions associated with food and goods consumed within the city but produced elsewhere, and jet fuel loaded into airplanes at the city's airports. We

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http://dx.doi.org/10.1016/j.esd.2014.06.006
0973-0826/

focused on buildings since they are responsible for 75% of the city's greenhouse gas emissions (Inventory).

We described NYC buildings in a way that allows us to calculate total current and future emissions of greenhouse gases. To do this we selected eight types of buildings that spanned the typical structures of the city. We then defined the characteristics of these building types, using data from the NYC Department of City Planning's PLUTO database (NYC Department of City Planning, 2011) 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 allowed us to scale the fuel, electricity usage, and associated emissions of individual buildings up to citywide levels for comparison with Inventory values. We also determined the dimensions for each building that would make them most representative of that building type as described below.

We then prepared detailed models of each of these buildings using the eQUEST building energy simulation program (eQUEST, 2013), and adjusted the thermal and energy 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 NYC: residential, commercial, industrial, and institutional. Given the limitations on available data, we subsumed all nonresidential buildings into one category, which we refer to as "commercial". Table 1 presents the basic characteristics of our eight building models.

Building characteristics and populations

Several steps were needed to ensure that each of our models represented a significant amount of floor space in NYC, 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 each of the building lots in PLUTO could be allocated to one of the eight 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 the correct number for the lot, but other characteristics, such as height and footprint, describe the "principal building" on the lot. Our models match the characteristics of the "principle building," but our scaling was done using the total floor area for the lots.

Although PLUTO is based on NYC tax and real estate sales records, we know that it must contain errors. However, there is no comparable data against which to test it, and it is used to validate less accurate data sets (Kontokosta, 2012). Given the many uncertainties implicit in projecting over 35 years, we have taken the PLUTO data as accurate.

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, and are summarized in Table 2 and Fig. 1.

- Lots were deemed residential if 50% or more of the total building floor area was listed as residential and commercial if less than 50%.
- Based on PLUTO data, buildings with seven stories or fewer were considered "low-rise", and those with eight or more stories, "high-rise."
- Smaller residential buildings were classified as row houses if classified as "attached" or "semi-attached" in PLUTO, and as 1–2 family houses or residential low-rise (based on size) if "detached."
- PLUTO contains no information regarding building construction materials, and no other citywide information was readily available. To distinguish construction types, we used "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 a surrogate since curtain wall construction has been in use since the 1960s.

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 category and dividing the total floor area by the number of buildings. These data are shown in Table 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 1–2 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. The "L" and "U" shapes were necessary to ensure that all rooms in residential buildings had windows.

Building simulation

eQUEST is a widely used and comprehensive building simulation modeling tool. Able to represent many construction types, equipment choices, and building characteristics, it calculates the thermal energy gained or lost and the equipment operations necessary to maintain specified indoor conditions. The software calculates the total energy used over one year using Typical Meteorological Year weather files (TMY2; Crawley and Huang, 1997) by performing 8760 energy balances for the building, one for each hour of the year.

The construction techniques modeled in each building type were typical for such buildings, but were adjusted to calibrate energy use to

Table 1
Characteristics of building models.

Type	Stories above ground	Area above ground		Residential units	Construction
		m^2	sf		
1–2 family house	2	126	1352	1–2	Wood frame
Row house	3	185	1992	2	Masonry
Low-rise residential	4	795	8558	9	Masonry
Masonry high-rise residential	15	11,424	122,972	117	Masonry — punch windows
Window wall high-rise residential	26	17,168	184,793	142	Floor-to-ceiling glazing
Low-rise commercial	2	1409	15,170	N/A	Masonry
Masonry high-rise commercial	17	21,298	229,249	N/A	Masonry — punch windows
Curtain wall high-rise commercial	21	17,912	192,808	N/A	Steel frame/curtain wall

Table 2
Criteria for classification of citywide building area.

Type	Stories	Area above ground		Period	Buildings	Citywide area	
		m^2	sf			10^6 m^2	10^6 sf
1–2 family house	1–3	<280	<3001	All	340,273	43	460
Row house	1–4	<465	<5001	All	389,887	72	777
Low-rise residential	1–7 (excluding 1–2 family and row house)			All	170,714	136	1461
Masonry high-rise residential	8–150	N/A		1700–1999	6363	73	782
	8–12	N/A		2000–2010			
Window wall high-rise residential	13–150	N/A		2000–2010	388	7	72
Low-rise commercial	1–7	N/A		All	69,352	98	1052
Masonry high-rise commercial	8–150	N/A		1700–1999	2941	63	674
Curtain wall high-rise commercial	8–150	N/A		2000–2010	271	5	52

citywide totals. Several key parameters for each building are shown in Table 3. All buildings were assumed to have double-glazed windows or curtain walls, and to use gas for cooking and laundry dryers. Residential lighting was mostly incandescent, while commercial lighting was all fluorescent (Global Energy Partners, 2010).

Energy use

Every building consumes energy for space heating and cooling, 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 ensured that the simulated energy consumption agreed with a variety of data sources, including:

- The Inventory (both fuel use and emissions)
- NYC Benchmarking results (City of New York, 2012)
- A detailed usage study by Consolidated Edison (Global Energy Partners, 2010)
- Internal eQUEST default values for some quantities such as pumping energy
- Studies of energy use in buildings from the US Energy Information Administration (Commercial Building Energy Consumption Survey, 2003; Residential Energy Consumption Survey, 2009; U.S. Department of Energy, 2011).

The overall goal was to develop eight model buildings that when looked at as individual buildings could reasonably represent the operating characteristics of actual buildings of that type, and would reproduce the fuel use and emissions reported in the Inventory 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. Several aspects of this process follow.

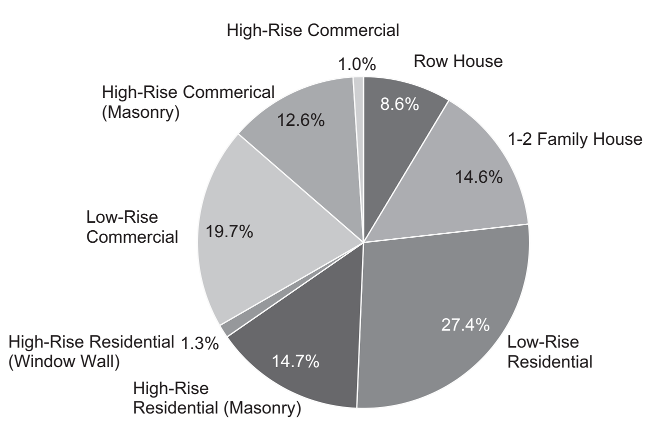

Fig. 1. Allocation of building floor area by building function.

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 Edison steam, as shown in Table 3. Rather than create separate eQUEST models for each heating system, we created one all-electric model of each building and used it to find the actual heating and hot water loads. Then, externally to eQUEST, we calculated fuel use for each type of heat used in each building, incorporating standard assumptions on the efficiency of each system, verified as discussed below.

Table 3 includes a column indicating the source EUI we found for each building model. We did not use the standard EPA source/site ratio of 3.14 (US EPA, 2014) since it is inaccurate for NYC due to substantial nuclear and hydropower supplies. Data from the Inventory show that the ratio for NYC in 2010 was 2.87, and we used this ratio in calculating source EUIs in 2010 for Table 3.

Emission summation

The fuel and electricity use for each building model was then scaled up to represent usage of electricity and each fuel from all the buildings of 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 building 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 (summed over building types to match the Inventory categories) to the Inventory totals provided the constraints that allowed us to determine the fuel splits in each building type as well as make final adjustments to building characteristics such as infiltration, insulation, and the efficiency of the fuel-using equipment.

The result of this exercise was a full-scale model of building energy consumption and emissions in NYC based on eight building types, detailed data on the characteristics of buildings, and computer models of the energy performance of the eight building types. Calculated fuel, electric use, and emissions for the entire city agreed with those in the Inventory to 1% or less. As described in succeeding sections, this model was then used to show how energy use in the building sector could be drastically reduced.

Accuracy

We have constructed a model of New York City based on building modeling and gross energy use statistics for the city. It is fair to ask how accurate this is. Since our building models were "tuned" to match the city-wide statistical data (±1%), the uncertainty lies in how different our base building models might be, for instance how much uncertainty there might be in amounts of insulation or infiltration, when compared to the actual building stock. We have already stipulated that we assume the PLUTO data is accurate, and we have substantial confidence in the Inventory data, since it is based on commodity sales records, and there is no substantial black market in fuel or electricity.

Table 3
Energy characteristics of building models.

Type	Glazed fraction	AC type	Plug loads		Main fuel types[a]	Source EUI	
			W/m^2	W/sf		kWh/m^2	kBtu/sf
1–2 family house	15%	Window	7.5	0.7	#2 oil, gas, electric	483	153
Row house	30%	Window	6.5	0.6	#2 oil, gas, electric	454	144
Low-rise residential	30%	Window	6.5	0.6	Gas, #2 oil, #6 oil, #4 oil, electric	429	136
Masonry high-rise residential	30%	Window	7.5	0.7	Gas, #6 oil, steam, #4 oil, #2 oil, electric	356	113
Window wall high-rise residential	50%	PTAC	7.5	0.7	Electric, gas	429	136
Low-rise commercial	30%	Rooftop	11	1	Gas, #2 oil, steam, electric, #4 oil, #6 oil	915	290
Masonry high-rise commercial	30%	Central	14	1.3	Gas, #6 oil, steam, #2 oil, #4 oil, electric	685	217
Curtain wall high-rise commercial	60%	Central	14	1.3	Gas	700	222
Data source	Expert opinion	(Global Energy Partners, 2010)			Iterative fit to Inventory data	Modeling results	

[a] Electricity is used for heat in less than 3% of buildings.

In our building classification scheme, most allocations to one of our eight building types are unambiguous within any limits on PLUTO's accuracy. However, there are two parameters – the fraction of high-rise commercial buildings that are curtain wall and the fraction of high-rise residential buildings that are window wall – that are based on expert opinion rather than PLUTO or other data and therefore uncertain. How would our building definitions change if there were more curtain wall or window wall buildings than we assumed?

If we assume that the fraction of high-rise residential buildings that are window wall construction is 50% higher than our expert estimate (12.6% instead of 8.4%), total energy consumed by both types would rise. But our constraint is that the total can't rise, since it is established by the Inventory and Benchmarking results. So if the window wall fraction was higher, the energy use per square foot would have to change in both window wall and masonry residential buildings. For this 50% increase in the window wall fraction, one can use the energy data presented below to show that energy use in the two building types must increase by about 1%. The comparable shift for a 50% increase in the fraction of commercial buildings with curtain walls is 0.1%, since the two types are more similar in base energy use. These shifts would be accommodated in the modeling process by very minor changes in insulation levels, infiltration, or comparable building characteristics. They are small enough to have no measurable effect on the improved buildings we model to determine 2050 energy needs.

Reductions in building emissions

We used a two-step process to determine the energy use of buildings in 2050. First, we used available projections of population and employment to estimate total future building area corresponding to each of our eight models, so that our results for each model could be scaled up to the areas in the 2050 city. 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 switch to all-electric provisioning of remaining services.

Approaches to emission reductions

To determine citywide use of carbon-free electricity in buildings after fuel use is eliminated, we needed projections for the building population in 2050. 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 deep retrofits will provide for a carbon-free future, we treat all 2050 buildings as the same within each building type. Whether a commercial high-rise building was built in 1970 and then retrofitted in the 2020–2050 time frame, or will be newly constructed in 2040, it is represented by the same eQUEST model. So we do not take advantage of the many ways a new structure can easily incorporate measures that are expensive or impossible in retrofits. Because a significant number of buildings will be built under increasingly stringent energy codes and will incorporate these improvements, our approach is intrinsically conservative.

Population and employment projections for 2050

NYC 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 Table 4 and discussed below.

The New York Metropolitan Transportation Council (NYMTC, 2011a, b) provided population and employment forecasts to 2040. Following a suggestion from 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 since it is unclear that 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. From 2010 PLUTO data, we calculated a residential floor area density of 434 sf (~40 m^2)/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 total residential building area that will exist in 2050, representing a 14% increase from 2010 to 2050. Accordingly, citywide floor areas for the 1–2 family houses, row houses, and low-rise residential buildings were increased by 14%.

Although they currently dominate new building starts, the window wall high-rise residential structure is an intrinsically poor design from an energy perspective. We assumed that building codes will advance sufficiently to ensure that no more are built after 2020 and that all residential high-rise construction after 2020 will be masonry or its thermal equivalent. The result is that the citywide area for masonry high-rise residential buildings is 12% above its 2010 value, and that for window wall construction is 40% above its 2010 value. These non-intuitive percentage increases occur because there are many existing high-rise masonry buildings, and relatively few window wall buildings. 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 over a 35 year future, zoning requirements and real estate values are essentially unknowable, so we used the simplest available assumption.

Table 4
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%

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 sf (~36 m^2) per employee. This value was decreased by 1% every five years, as shifting job categories and economic pressure result in smaller workspaces. Even with this slowed growth, we anticipate a 19% increase in commercial building area, the same for each building type, from 2010 to 2050.

We did not repeat our calculations for a spectrum of possible futures. Lower projections exist (9% by 2040, PAD, 2011), but are based solely on demographic data and do not account for potential changes in economic activity. Greater growth would lead to greater energy requirements, ameliorated by more inherently efficient new construction, but would not affect the feasibility of the future we present as possible. Lower growth would make achieving our future easier. Establishing that feasibility is our primary thrust, and variations in the 2050 building area or employment away from this plausible but uncertain future would complicate that presentation without adding useful information.

Building sector energy reduction measures and savings

Overview

Reductions of energy use in and emissions from buildings are achieved by a series of energy efficiency measures. The impact was estimated by applying these measures to the 2010 eQUEST models described previously. A summary of the measures follows.

Our analysis assumed that no significant lifestyle changes take place. Thermostat setpoints were ~70 °F in winter and ~75 °F in summer for both 2010 and 2050, although people might modify them 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. Smart controls such as occupancy sensors can dramatically lower heating and cooling loads, but we have used only standard clock-driven setbacks. All the technologies used are available today, although some are not yet common. Some might consider our exclusion of window wall buildings a “lifestyle change”, but the longevity of this style is questionable (Urban Green Council, 2013b).

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 reduction case below, indicating the sensitivity of future energy needs to our assumptions on building efficiency improvements.

Minimize air exchange losses

Air leaks in buildings occur in numerous places, including elevator and stairwell vents, cracks, gaps around windows and doors; and through leaks in the ductwork. Air sealing, ventilation control, and heat or energy recovery systems can minimize these losses.

For each 2050 building model, the infiltration rate was reduced to 0.2 air changes per hour (ACH) at atmospheric temperature and pressure (ATP). Air infiltration in a passive house is typically no greater than 0.03 ACH at ATP (What is a Passive House?, 2013). For the less rigorous sensitivity study, the infiltration rate was relaxed to 0.4 ACH at ATP. With either of these low levels of infiltration, healthy air must be maintained by mechanical ventilation.

Less vision glass

Today's high-rise curtain wall and window wall buildings commonly have greater than 50% 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 (Mayer, 2013) and that the vision glazing would then be reduced to 50% or less of the total exposed wall, replaced by spandrel glass that can be well insulated while preserving the exterior appearance.

Increased insulation

Current levels of thermal resistance in the opaque portions of the walls of NYC buildings range from the R-2 to R-4 ft^2 °F hr/Btu (R-0.35 to R-0.7 m^2 °C/W) levels typical of uninsulated brick and wood frame structures to values in the range of R-8 to R-10 (R-1.4 to R-1.8) for modern, code-compliant buildings. Roof insulation is typically higher, with current code requirements of R-20 to R-38 (R-3.5 to R-6.7) in commercial buildings and R-38 (R-6.7) in smaller residential structures. Our 2010 building models incorporated relatively low levels of insulation, consistent with these ranges but tuned to give EUIs and emissions matching those of the actual 2010 city. These generally fell well short of current code requirements.

For 2050, all residential buildings were upgraded to R-50 (R-8.8) roofs, with R-30 (R-5.3) walls on the 1–2 family house and R-20 (R-3.5) walls on other residential buildings. Opaque areas on commercial buildings were upgraded to R-30, and R-11 (R-1.9) was added to all walls below ground.

There are legitimate esthetic 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 is added to provide an average resistance of R-20. Second, the insulation can most easily and effectively be added to the building's exterior, but when this is not appropriate (as for an architecturally pleasing front façade), insulation can be added to the interior of the wall. Finally, R-20 and R-50 represent average values, while of course some buildings will be above the average and some below. A recent report (Neuhauser, 2013) describes in detail methods, experiences, and challenges in applying substantial exterior insulation to existing masonry buildings while another (Clark et al., 2013) reports on substantial success in a similar effort.

For the less rigorous scenario, roof insulation was modeled at R-35 (R-6.2) and wall insulation at R-21 (R-3.7) on the 1–2 family house and R-14 (R-2.5) on the other buildings.

Incorporate triple glazing

Triple glazed (three pane) windows were also utilized to reduce heat transfer in all buildings. With a high-quality triple glazed window or curtain wall, U-0.20 (U-1.1) is readily achievable, and that is the glazing represented in all 2050 building models. 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.

Add sunshades to south windows

Sunshades control the amount of direct sunlight allowed to pass through a building's windows, reducing cooling equipment loads. Shades are available that move seasonally or daily, or in a variety of complex configurations. For our 2050 models, we used simple, static sunshades three feet (0.3 m) in length, installed horizontally, directly above the south-facing windows of all buildings.

Energy recovery ventilation

The effective national standard for ventilation (ASHRAE, 2013) requires certain minimum airflow rates based on building area and occupancy, which would not be met solely by infiltration in our 2050 buildings following extensive air sealing. To compensate, we used air exchange rates double those of the ASHRAE standard. For the residential buildings, the forced airflow rates were modeled as 0.12 cfm/sf plus 10 cfm/person (0.61 lps/m^2 and 4.7 lps/person). For commercial buildings, the flow rates were modeled as 0.24 cfm/sf plus 20 cfm/person (1.22 lps/m^2 and 9.4 lps/person). For some residential settings, building code would permit various lower rates but since HVAC energy consumption met our targets at this uniform level of ventilation, 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 in all buildings. Individual ERV units serviced each apartment, while the commercial buildings were ventilated centrally. The ERV systems were modeled with an overall efficiency of 75%.

Mini-split heat pumps for most residential HVAC

Window and sleeve air conditioners are notoriously leaky (Urban Green Council, 2011). Leaks can be prevented by systems that separate the outdoor condenser unit from the indoor evaporator, connecting them only by tubes for the refrigerant and condensate water. These are standard systems for centrally cooled single-family homes and are available in apartment sizes, colloquially called "mini-splits." They are also available as heat pumps. This technology allows complete electrification of heating as well as cooling, and also provides a way to remove residential heating from central building services and put it in the control and at the expense of the resident, aligning individual cost savings with energy reduction. We assumed individual apartment installations in all residential buildings except the masonry high-rise, which was heated and cooled centrally.

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 available; getting the industry to produce smaller air handlers is a challenge, and the only area where today's equipment is not appropriate to our models. Using available air handlers would result in systems at least double the required capacity. We chose cooling and heating coefficients of performance (COP) of 4.7 and 3.6, which are currently available.

Water-source and ground-source heat pumps

Heating and cooling was provided in our commercial building models and the high-rise masonry residential building model with ground-source heat pumps. These systems circulate water through deep vertical wells and deposit excess heat in the earth during the summer, while retrieving it to provide space heat in the winter. This technology is now well known in NYC, having been implemented in several buildings (NYC Department of Design and Construction, 2012). It is still expensive and drilling the wells is disruptive, but there are few significant technical impediments to its deployment.

Air-source heat pumps for domestic hot water

Domestic hot water (DHW) needs in NYC are commonly met by burning a fossil fuel, or in some cases, with an electric resistance hot water heater. An air-source heat pump (ASHP) withdraws thermal energy from the air surrounding the device and uses it to provide DHW (Aldrich and Shapiro, 2012). Because the water is heated only to 124–130 °F (51–54 °C), the machines operate at a coefficient of performance of 4.0. Located in the conditioned space, they provide substantial "free" cooling and dehumidification in summer, while adding to the heating load in winter. These interactions are accounted for in the eQUEST modeling, and these units supply DHW in all building models, except for that supplied by the technology in the next section. Recirculation losses are eliminated since each apartment has its own hot water source. And as is the case for heat, the apartment residents are financially responsible for their own consumption.

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. This heat can supply DHW using only the power required for a circulation pump, while the ASHP must operate a compressor. Accordingly, the condenser heat 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 (RETScreen International, 2013), 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, solar photovoltaics that help power the air-source heat pumps were a better use of rooftop area.

Appliances and internal loads

We took several steps to lower internal electrical and gas loads. For lighting, data from the Con Edison study (Rohmund and Wikler, 2010) 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 lm/W, compact fluorescent lamps at 75, and incandescent lamps at 15, a total number of lumens per dwelling unit (residential) or per square foot (commercial) could be calculated from an assumption of how many "screw in" lamps were incandescent. 2050 lighting power densities were then created by requiring the same lumen density, but supplying it with 100 lm-per-watt fixtures without specifying the type (high-performance fluorescent, light-emitting diode [LED], etc.). Annual lighting energy use was also reduced by 20% to account for dimming, bi-level, and occupancy controls. For the residential buildings, an assumption that 70% of "screw-in" lamps were incandescent led to a 73% reduction in lighting energy, while for commercial, an assumption that 50% of the much smaller number of "screw-in" lamps were incandescent led to a 46% reduction. A similar treatment of external lighting led to 66% reductions for residential buildings and 49% reductions for commercial buildings.

The treatment of "miscellaneous equipment" in the residential sector is shown in Table 5. The 2010 usage numbers are from a comprehensive study carried out for Con Edison (Global Energy Partners, 2010). For 2050, all the reductions are based on known technical improvements, most of which are available in the market today. In many cases we simply assumed current Energy star standards would be met. Gas stoves and dryers are replaced with electrical induction stoves and heat pump (no exhaust) dryers.

Commercial equipment energy use reductions are shown in Table 6. The 2010 data is again from the Con Edison study (Global Energy Partners, 2010). 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

Table 5
Annual residential equipment usage.

Equipment type	2010	2050	
	kWh/dwelling unit	Approximate reduction	kWh/dwelling unit
Refrigerator	789	50%	400
Clothes washer (electric)	95	25%	71
Dishwasher (electric)	83	25%	62
Personal computer	273	0%	273
Color TV	217	25%	163
Other electronics	81	0%	81
Other miscellaneous	865	29%	615[a]
Dryer: 2010 gas/2050 heat pump	692	75%	173
Stove: 2010 gas/2050 induction	1040	52%	498
Total	4135	–	2336

[a] Includes replacement of television cable boxes for 250 kWh savings.

Table 6
Annual commercial equipment usage.

Equipment type		2010 kWh/m^2	2010 kWh/sf	Approximate reduction	2050 kWh/m^2	2050 kWh/sf
Refrigeration	Reach-in	11	1.0	50%	5.4	0.50
	Walk-in	38	3.5	50%	19	1.74
Food service		25	2.3	25%	19	1.76
Office equipment	Personal computer	3.8	0.35	0%	3.8	0.35
	Server	2.6	0.24	25%	1.9	0.18
	Monitor	4.3	0.40	25%	3.2	0.30
	Printer/copier	1.1	0.10	25%	0.9	0.08
	Other	3.9	0.36	25%	2.9	0.27
Total		89	8.3	–	56	5.2

data. The energy use of computers per calculation has been shown to be halved every eighteen months (The Economist Online, 2011), a reduction far more dramatic than our assumptions. At a more practical level, many desktop computers use 50–60% of their full power when nominally asleep due to faulty settings, a problem readily addressed through education, more aggressive default settings, or more sophisticated controls.

Photovoltaics

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 (2009) estimates the average solar insolation in NYC as approximately 4.34 kWh/m^2 per day for the best deployment of a stationary system, a flat solar panel tilted at an angle equal to latitude.

Solar panels were added to the rooftops of each of our building models for 2050, based on the technical specifications from the best units available on the market today, with panel efficiencies of 20%. As solar panels produce direct current (DC) power, an inverter was required, at a conversion efficiency of 90%.

Enough solar collectors were added to cover 50% of the available rooftop area on each building, leaving room for elevator houses, fire department access, and other uses. For modeling purposes, each building model was allowed unshadowed access to the solar resource, but we assumed that only half the actual buildings of each type had access to sunshine, so that collectors were only added to one-half of the roofs, reducing the scaling factor by 50%. The resulting citywide capacity and generation, shown in Table 7, are about 25% greater than that found by the New York City Solar Map (NYC Solar Map) because our collectors are more efficient than the lower cost 2010 devices they modeled.

Cost estimates

In order to get a sense of the economic feasibility of enacting the measures described above, we developed an expense model and used it to develop cost estimates for the retrofits. These estimates were then scaled up to provide an overall estimate of the cost to retrofit the entire city, starting at the year 2015. Finally, we estimated the anticipated savings resulting from the retrofits to find what portion of the entire project cost might be offset 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 currently available technologies in estimating costs. Many things can change over the next two or three decades, and the costs of some measures may drop dramatically. It is 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.

Other measures are modifications to actions that would be required to keep a building in good repair regardless of other considerations. Many items wear out and must be replaced, especially when considering a 35 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

Table 7
Electric use and source energy use intensities in 2050 buildings.

Building type	2050 building energy usage					Impact of photovoltaics[a]	
	2050/2010 source EUI[b]		2050/2050 source EUI[c]		Total electric	PV production	Net electric use
	kWh/m^2	kBtu/sf	kWh/m^2	kBtu/sf	MWh/yr	MWh/yr	MWh/yr
1–2 family house	200	64	72	23	9.0	7.2	1.7
Row house	220	70	78	25	15	8.4	6.1
Low-rise residential	220	70	77	25	61	28	34
Masonry high-rise residential	140	45	50	16	580	80	500
Window wall high-rise residential	165	53	59	19	1020	72	950
Low-rise commercial	390	123	140	44	195	100	95
Masonry high-rise commercial	270	87	98	31	2100	180	1910
Curtain wall high-rise commercial	270	87	98	31	1800	120	1640

[a] Production and net use for the 50% of buildings citywide to which PV was added.
[b] 2050 building energy use with source EUI based on 2010 generation fuel mix.
[c] 2050 building energy use with source EUI based on 2050 generation fuel mix.

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 costs for each building type and for NYC as a whole are reported in the "Results" section below, and the estimates for each measure are in Appendix A.

Results

Final building electricity requirements

The building models were run again with the measures in the Building sector energy reduction measures and savings section implemented, and the resulting EUIs are presented in Table 7. Here, the total electric energy consumed in each modeled building is shown in column 6, with PV production for that building (assuming it is one of the 50% that received PVs) in column 7, followed by the net energy the building demands from the grid in one year in column 8.

In 2010, the NYC building stock was responsible for the emission of 40.6 million metric tons of GHGs, with the source EUIs shown in Table 3. To show the impact of the energy efficiency measures alone, columns 2 and 3 of Table 7 show the EUIs the 2050 buildings would have if operated under the 2010 fuel mix. In this scenario, the buildings would be responsible for the emission of just 16 million metric tons of CO_2e — a 61% reduction in GHG emissions based on efficiency improvements alone.

Although these modeling results indicate dramatic reductions in energy use, they are entirely achievable, and have been demonstrated in real buildings. Table 7 shows an EUI of 70 kBtu/ft^2 for the row house using the 2010 generation mix. A near-Passive House retrofit in New York City (Passipedia, 2013) has an EUI of 35.2 kBtu/ft^2, one-half of what we are proposing. A commercial office tower in Vienna, Austria has met the full Passive House requirement of less than 38 kBtu/sf (Leigh, 2013) at a 5.4% cost increment.

However, if the electricity in 2050 is carbon-free, site energy and source energy are equivalent, and give rise to the final EUIs in columns 4 and 5 of Table 7. 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 that issue in this work.

Electric generation needed

When the electric energy needed to power the buildings was summed across building sectors, the total requirements to maintain the city's buildings for one year were 50.6 TWh, about equal to the 2010 consumption of 49.5 TWh. This is gross energy needed by buildings, independent of production from photovoltaic (PV) panels on roofs. On-site PV production produced 10.7 TWh in our scenario, reducing net building electric energy use to 39.9 TWh.

As discussed in the Overview section, we investigated a second, less rigorous scenario for our building energy reduction measures. In this case, infiltration was allowed to double to 0.4 air changes per hour, and insulation R-values were lowered by about 30%. The results are in Table 8, and show that the smaller buildings, dominated by envelope losses, are more affected by the changed parameters.

As a result, the gross electric energy needed for buildings increased by about 6% to 53.7 TWh, or 43.0 TWh after deducting PV production. This modest increase implies that we may be able to tolerate a less rigorous program of building improvement than that modeled in our base case, but increased demand (below) may pose a greater challenge.

Although producing this much carbon-free electricity is challenging, it is far from impossible. Several studies have already been carried out at the national and global scale (Delucchi and Jacobson, 2011; Fthenakis et al., 2009; Jacobson and Delucchi, 2011) and for New York State (Jacobson et al., 2013). Denmark now gets 28% of its electric energy from windmills and aims for 50% by 2020 (Denmark, 2014). NYC buildings will need only an additional 20.9 TWh if the city can maintain access to the roughly 19 TWh of carbon-free power that the Inventory reports is currently used. This 20.9 TWh can be supplied by some mix of wind (especially off-shore), Canadian hydro, PV arrays on roads, parking lots, and other open space and/or up to three nuclear generation stations. Somewhat greater capacity would be needed in the relaxed case. We have not studied and do not advocate for any of these alternatives; our point is that barriers to sufficient carbon-free generation are political and economic, and subject to modification as the cost of climate change becomes clearer.

Peak loads and impact on the electric grid

Even if supplying the needed carbon-free electricity in 2050 is plausible, peak demand and load–supply temporal matches present separate challenges. 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%, meaning a 77% 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 modeled 2010 building demands to the building peak load of 7960 MW in 2010 reported by Con Edison (New York Independent System Operator, 2012; Summit Blue Consulting, 2008). It is clearly 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% increase over total 2010 building load. This would correspond to a substantial decrease in the system load factor, from 73% to 46%. This result is not surprising, since heat pumps generate a peaked load like air conditioners, but based on heating

Table 8
2050 building source EUIs, base and relaxed scenarios.

Building type	2050 EUIs		
	Base case kBtu/sf	Relaxed case kBtu/sf	Change
1–2 family house	23	25	9.5%
Row house	25	27	9.8%
Low-rise residential	25	26	8.3%
Masonry high-rise residential	16	18	10.1%
Window wall high-rise residential	19	21	9.2%
Low-rise commercial	44	45	3.1%
Masonry high-rise commercial	31	32	2.5%
Curtain wall high-rise commercial	31	32	3.6%

Table 9
Electric energy and peak demand in buildings.

Quantity	2010	2050 base case	2050 relaxed case
Building electric energy consumption (TWh)	50.6	50.6	53.7
PV production (TWh)	0.0	10.7	10.7
Net electric energy consumption (TWh)	50.6	39.9	43.0
Peak demand — 2010-summer, 2050-winter night (GW)	8.0	12.6	14.0

Table 10
Costs of proposed retrofit measures.

Building type	Incremental retrofit cost	Cost/unit	Cost/m^2	Cost/sf
1–2 family house	$26,100	$26,100	–	–
Row house	$31,700	$15,800	–	–
Low-rise residential	$180,000	$20,000	–	–
Masonry high-rise residential	$4,440,000	$38,000	–	–
Window wall high-rise residential	$4,210,000	$29,600	–	–
Low-rise commercial	$555,000	–	$394	$36.60
Masonry high-rise commercial	$6,970,000	–	$327	$30.40
Curtain wall high-rise commercial	$11,200,000	–	$624	$58.00

loads rather than cooling. Demand increases even more in the relaxed scenario. The results are presented in Table 9.

It is clear that a substantial increase in distribution capacity will be needed, as will a considerable amount of storage capability, both electric and in-building thermal storage. The storage will have to match the day-time supply peak, generated in part by PV modules in winter sunshine, with the nighttime peak of the heating load. The cost of the expanded distribution system will impact the optimal balance between central and distributed storage. Peak loads could also be met in part by combustion plants fueled with more readily stored biomass. Finally, the extreme (75%) increase in demand for the relaxed case indicates that meeting peak demand may be more of a driver toward maximum retrofits than will the cost of carbon-free energy. These matters will be the subjects of future research.

Cost estimates for building improvements

The cost-estimating group of Lend Lease (US) Construction LMB, Inc. provided us with the cost estimates presented in this section. The estimates are summarized in Table 10, and a detailed accounting is included in Appendix A. Table 10 shows the costs of carrying out the retrofit options used in the building models for each building type. The costs were determined for the modeled buildings and would vary widely 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, these costs should be regarded as a first-pass estimate of average costs for each building class. In each case we present the incremental cost after credit for normal replacements.

Although the costs presented in Appendix A and summarized here are those used by a major contractor to bid jobs in 2010, their accuracy can be questioned. Since here they describe averages over large numbers of retrofits to different buildings, we have chosen to utilize assumptions that ensure that they are maximal costs when the retrofit of the entire city is considered. There are several reasons to expect that the actual costs incurred over the next 35 years will be lower than these:

- As energy efficiency measures become more common, the development of prefabricated systems and better materials will lower costs in this sector relative to others;
- These costs were for retrofits; for new construction, it will be far easier to specify and incorporate air sealing, insulation, ventilation ducting, and the other technologies we have incorporated; and
- New technologies, such as vacuum foam insulation and electrochromic windows, will outperform the currently available technologies we have utilized.

Consequently, we are confident that these costs represent upper limits on retrofit costs over the 35 year period we have examined (although they may not be upper limits today), and have not performed further sensitivity analysis with respect to retrofit costs.

Table 11
Financial savings in buildings.

Commodity	U.S. unit	Price/U.S. unit	Cost/MWh	Total energy bill
Commodity costs, 2015				
Electricity	MWh	$230	$230	$18.4 billion
Gas	Dekatherm	$13.30	$45	
Oil (#2, 4, & 6)	Gallon	$2.90	$68	
Steam	Million Btu	$25	$85	
Commodity costs, 2050				
Electricity	MWh	$250	$250	$10.8 billion

Costs totaled for NYC

The cost estimates of the Cost estimates for building improvements section were scaled up to develop an estimate of the total cost of retrofitting NYC using the ratio of total floor area for each building type to the floor area of that building model, as was done to calculate citywide 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, ~7% of the city's municipal budget or 0.4% 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. Again, this cost estimate is based on 2010 estimates and for many technologies, there is every reason to expect technical advances and market pull to reduce prices over time, in some cases dramatically.

The value of energy savings and 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 (McKinsey, 2009). But several others (for instance, the substantial insulation additions) 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. We 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 price in 2015 dollars (U.S. Energy Information Administration, 2013). This does not incorporate price increases that would flow from conversion of the electric system. Those increases would make building improvements more cost effective, but would represent other increased costs of the transition. All quantities are shown in Table 11. We found that a reduction in costs of 1.5% per year would reproduce this reduction over 35 years, and ascribed each 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% 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 3% constant dollar discount rate (Fuller and Petersen, 1996; Rushing et al., 2012). Also, the present value of the uniform capital outlays, discounted at 3%, is $94 billion, giving a present value of the savings that is 93% of the present value of the capital costs.

So under our baseline assumptions, the measures described above come close to paying for themselves, using standard, long-term economic methods (Fuller and Petersen, 1996; Rushing et al., 2012). 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.

Other savings have been ignored. For instance, we have taken no credit for the dramatic reductions in mortality and morbidity that will occur as fossil fuel combustion and the resultant air pollution are phased out. Others (Jacobson et al., 2013) have shown that removing combustion products from the air of New York State would pay for itself in health costs alone in sixteen years.

Consequently, 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 discussed earlier, and substantial fiscal benefits will accrue from the dramatic decline in air pollution. Under any plausible mix of these factors, the measures 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 the total costs 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 (which are not included here) will become ever more clear
- 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 (without mass transit components) will cost $4 billion (New NY Bridge, 2014), and the reconstruction of the World Trade Center will cost at least $4 billion (Brown, 2013). Current estimates of the cost of the damage from hurricane Sandy are over $50 billion (NOAA, 2013), incurred in one tragic event that may well be repeated regularly. On this scale, even a discounted outlay of $94 billion is completely consistent with the risks.

Employment impact

In addition to benefits to the climate and the potential for energy savings on par with the cost of proposed changes, the money used to institute the measures described here will create thousands of green jobs. The NYC Building Congress estimated a total of 112,400 construction jobs in NYC in 2010 (New York Building Congress, 2013). Our plan would create an ongoing demand for at least 11,000 additional construction jobs during the forty years, increasing employment by almost 10% from 2010 levels (New York Building Congress, 2013; RSMeans, 2012). For instance:

- 6500 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
- The installation of 99 million windows, 45 million square feet of window wall, and 31 million square feet of curtain wall will require 2700 construction jobs each year from 2015 to 2050
- 5.65 million residential apartments and 2.12 billion square feet of commercial floor area will require air sealing, requiring 1860 workers each year from 2015 to 2050.

Training and deploying this army of workers will be a major task in itself. Training programs are now underway, both within unions and independently, but have only reached a small fraction of the necessary work force (Urban Green Council, 2013a). The economic value of spending NYC money on local trades, people and construction, rather than sending it abroad or out of state for fossil fuels is obvious, and has been studied in depth in larger contexts (Barrett et al., 2002; Wei et al., 2010).

Conclusion

We have developed one pathway to greatly reduce energy use in the buildings of NYC, including the replacement of fuel-burning HVAC and hot water systems by electrically powered equivalents. This substantial decrease in energy use will make production of all electric power from carbon-free sources far more practical and cost-effective. However, the conversion to all-electric buildings whose demand peaks on winter nights will require the development of considerable energy storage capacity, substantial carbon-free power that is not solar, and increases in the capacity of the distribution system to meet an estimated 60% increase in peak demand.

Even if today's generation mix were retained, greenhouse gas emissions would be reduced by over 60% by these energy efficiency measures alone. Further, this reduction can be achieved at costs that are comparable to the expected savings when costs are amortized over twenty to thirty years, or over shorter periods if ancillary factors such as expected cost reductions, fuel or emissions price increases, or health benefits are included in the analysis. The potential of energy efficiency measures to lower our demand for energy is the key to a sustainable future.

Acknowledgments

We thank the Doris Duke Charitable Foundation for their support under Grant 2011050. The foundation had no role in this work other than funding. We also thank James Stawniczy, Joseph Esposito, and Raynor Rogers for cost estimates, Arpan Bakshi, Barry Fisher, Umit Sirt, and Michael Tillou for modeling assistance, and Eric Boorstyn, Paul Freitag, Ellen Honigstock, Laurie Kerr, Ken Levenson, Richard Rosen, Howard Slatkin, Paul Stoller, Russell Unger, and Marc Zuluaga for valuable comments and suggestions.

Appendix A. Detailed cost estimates

The unit costs of both conventional and innovative measures are presented in Tables A1 and A2 for each building type. The total cost of all appropriate measures in each building are presented in Tables A3 and A4. Air sealing ranged from relatively inexpensive, $2.30/sf ($25/m^2) for the high-rise buildings, to $6.00/sf ($65/m^2) for the low-rise residential, to $16.00/sf ($172/m^2) for the low-rise commercial building. Lend Lease 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 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.

One possibly significant cost has been omitted from our analysis. In order to install induction stoves and individual heat pumps in apartments, many buildings will require improvements to their internal wiring systems. This factor was omitted both because the vast variation in existing buildings makes it very difficult to estimate the cost in any “typical” situation, and because many electrical systems will require repair or upgrade over the thirty-five year time horizon even without the introduction of these measures.

Table A1
Envelope cost estimates.[a]

Building	Area used: cost category	Envelope: Air-seal units (res) or building (com) to 0.1 ACH	During re-skinning, lower vision glass to 50% max	Insulate opaque areas (Res: R50 roof, R20 walls; Com: R30 all exposed surfaces)	Triple glaze all fenestration with U ≤ 0.20 polymer film triple glazing	Add 3′–6″ sunshades to south windows
		Floor area	Floor area	Opaque area	Glazed area	Floor area
1–2 family house	Standard replacement				$35	
	High-performance item	$6.00		$2.60	$50	$1.50
	Increment				$15	
Row house	Standard replacement				$35	
	High-performance item	$6.00		$2.60	$50	$1.50
	Increment				$15	
Low-rise residential	Standard replacement				$35	
	High-performance item	$6.00		$2.60	$50	$1.50
	Increment				$15	
Masonry high-rise residential	Standard Replacement				$65	
	High-performance item	$3.60		$2.60	$90	$2.05
	Increment				$25	
Window wall high-rise residential	Standard replacement				$75	
	High-performance item	$2.30		$2.60	$100	$3.00
	Increment				$25	
Low-rise commercial	Standard replacement				$65	
	High-performance item	$16.03		$2.60	$90	$2.75
	Increment				$25	
Masonry High-rise commercial	Standard replacement				$65	
	High-performance item	$2.28		$2.60	$90	$3.25
	Increment				$25	
Curtain wall high-rise commercial	Standard replacement				$120	
	High-performance item	$2.31	$5.00	$1.50	$150	$4.00
	Increment				$30	

[a] Estimate are in $/ft^2; multiply by 10.8 for $/m^2.

Table A2
HVAC and DHW cost estimates.[a]

Building	Area used: cost category	Space heat/cool: Energy recovery ventilation (ERV)	Space heat/cool: Mini-split heat pumps	Space heat/cool: Ground source heat pumps, hydronic H&C distribution	DHW: DHW loop on GCHP	DHW: DHW HP operating in conditioned space	DHW: Heat recovery for DHW on ACs
		Floor area	Floor area	Floor area	Floor area	Floor area	Floor area
1–2 family house	Standard replacement		$3.85				
	High-performance item	$1.50	$2.60			$2.00	$1.00
	Increment		−$1.25				
Row house	Standard replacement		$3.85				
	High-performance item	$1.50	$2.60			$2.00	$1.00
	Increment		−$1.25				
Low-rise residential	Standard replacement		$3.85				
	High-performance item	$2.99	$2.60			$2.00	$1.25
	Increment		−$1.25				
Masonry high-rise residential	Standard replacement			$4			
	High-performance item	$2.99		$22[b]	$2.00		$0.10
	Increment			$18			
Window wall high-rise residential	Standard replacement		$8.00				
	High-performance item	$2.99	$3.60			$2.00	$0.10
	Increment		−$4.40				
Low-rise commercial	Standard replacement			$11			
	High-performance item	$4.07		$30	$2.08		$1.85
	Increment			$19			
Masonry high-rise commercial	Standard replacement			$12			
	High-performance item	$5.99		$26	$1.80		$0.11
	Increment			$14			
Curtain wall high-rise commercial	Standard replacement			$12			
	High-performance item	$5.99		$28	$1.80		$0.11
	Increment			$16			

[a] Estimates are in $/ft^2; multiply by 10.8 for $/m^2.
[b] Lend Lease priced the geothermal system at $17/sf ($183/m^2) for the entire system minus the hydronic distribution. Based on a recent NYC steam-to-hydronic conversion (Rieber, 2012), we have added $5/sf ($54/m^2) to cover partial to full replacement of piping.

Table A3
Building cost estimates.

Envelope						
Building	Cost category	Air-seal apartments or building	Lower vision glass to 50% max.	Insulate opaque areas	Triple glaze all fenestration	Add 3′ sunshades to south windows
1–2 family house	Standard				$11,700	
	Proposed	$8110		$6550	$16,800	$2030
	Increment				$5030	
Row house	Standard				$14,200	
	Proposed	$12,000		$4180	$20,200	$2990
	Increment				$6070	
Low-rise residential	Standard				$112,000	
	Proposed	$51,400		$24,900	$159,000	$12,800
	Increment				$47,800	
Masonry high-rise residential	Standard				$1,850,000	
	Proposed	$443,000		$194,000	$2,560,000	$252,000
	Increment				$711,000	
Window wall high-rise residential	Standard				$6,100,000	
	Proposed	$425,000		$230,000	$8,130,000	$554,000
	Increment:				$2,030,000	
Low-rise commercial	Standard				$175,000	
	Proposed	$243,000		$36,100	$243,000	$41,700
	Increment				$67,500	
Masonry high-rise commercial	Standard				$2,450,000	
	Proposed	$523,000		$263,000	$3,390,000	$745,000
	Increment:				$941,000	
Curtain wall high-rise commercial	Standard				$18,900,000	
	Proposed	$445,000	$964,000	$108,000	$23,700,000	$771,000
	Increment				$4,730,000	

Table A4
Building cost estimates.

		Space heat/cool			DHW		
Building	Cost category	Energy recovery ventilation (ERV)	Mini-split heat pumps[a]	Ground source heat pumps, hydronic distribution	DHW loop on GCHP	DHW air source HP	Heat recovery for DHW on ACs
1–2 family house	Standard		$5210				
	Proposed	$2030	$3520			$2700	$1350
	Increment		−$1690				
Row house	Standard		$7, 700				
	Proposed	$2990	$5200			$3990	$1990
	Increment		−$2500				
Low-rise residential	Standard		$33,000				
	Proposed	$25,600	$22,000			$17,100	$10,700
	Increment		−$11,000				
Masonry high-rise residential	Standard			$490,000			
	Proposed	$368,000		$2,710,000	$246,000		$12,300
	Increment			$2,220,000			
Window wall high-rise residential	Standard		$1,480,000				
	Proposed	$553,000	$665,000			$612,000	$612,000
	Increment		−$815,000				
Low-rise commercial	Standard			$167,000			
	Proposed	$61,700		$455,000	$31,600		$28,100
	Increment			$288,000			
Masonry high-rise commercial	Standard			$2,750,000			
	Proposed	$1,370,000		$5,960,000	$413,000		$25,200
	Increment			$3,210,000			
Curtain wall high-rise commercial	Standard			$2,310,000			
	Proposed	$1,150,000		$5,400,000	$347,000		$21,200
	Increment			$3,080,000			

[a] Mini-split heat pumps are less expensive than maintaining/replacing conventional central systems in these applications.

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