New York City Can Eliminate the Carbon Footprint of its Buildings by 2050

Daniel Wright, Pratt Institute
Richard Leigh, Jamie Kleinberg, Katie Abbott, and Jonah "Cecil" Scheib,
U.S. Green Building Council of New York

ABSTRACT

Climate scientists agree that a reduction in carbon emissions of at least 80% in the coming decades is necessary to make possible a future free of major disasters brought on by 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 in climate change mitigation by improving the energy efficiency of its building sector through implementing currently available (although underutilized) technologies. In our analysis, building energy use is reduced by 50-60%, but remains substantially greater than what would occur under Passive House standards. Technologies include both thermal load reduction and electrification of all building services. After eliminating fuel combustion, carbon-free electric energy roughly equal to the total electric energy used in 2010 would be consumed, but with a peak demand 60% higher than today's, establishing requirements for generation and distribution capacity and energy storage. Coupling these improvements with technically viable sources of carbon-free electric power can eliminate carbon emissions from NYC's buildings. Economic analysis of the building efficiency measures and associated savings shows them to be essentially cost-neutral over their lifetimes.

Introduction

Nearly all climate scientists (IPCC 2013; Hansen et al. 2013) agree 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 parts per million, which could maintain global temperature increases of less than 2°C (IPCC 2013; Union of Concerned Scientists 2007).

A key part to realizing this reduction is the elimination of carbon emissions from the built environment. In determining the feasibility of this goal, we have focused on what is possible in the building sector in NYC 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.

We did not examine year-by-year developments over the coming decades. Instead we examined the city as a whole, and looked in detail at the two endpoints, 2010 and 2050. This allows us to sketch a credible future that meets the reduction goal. However, specific and detailed trajectories must be developed to serve as a basis for specific policy proposals.

Analytic Process

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.

In this work we used the September 2011 release of the "Inventory of NYC Greenhouse Gas Emissions" ("Inventory"; City of New York 2011) to provide a detailed picture of emissions in 2010, which we used as our base year. Our study was restricted to Scope 1 and 2 emissions (CARB 2010) as reported in the Inventory.

We developed 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 city's PLUTO database (NYC DCP 2011) of 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. The citywide floor area divided by the model building floor area for each type gave us the ratios needed to scale the fuel, electricity usage, and associated emissions of individual buildings up to citywide levels for comparison with Inventory values.

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 scaled-up 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. We subsumed all non-residential buildings into one category, which we refer to as "commercial". Table 1 presents the basic characteristics of our eight building models. The derivation of the characteristics is explained below.

Table 1. Characteristics of building models

Type	Stories	Floor area (sf)	Units	Construction
1-2 Family house	2	1,352	1-2	Wood frame
Row house	3	1,992	2	Masonry
Low-rise residential	4	8,558	9	Masonry
Masonry high-rise residential	15	122,972	117	Masonry – punch windows
Window wall high-rise residential	26	184,793	142	Floor – ceiling glazing
Low-rise commercial	2	15,170	N/A	Masonry
Masonry high-rise commercial	17	229,249	N/A	Masonry – punch windows
Curtain wall high-rise commercial	21	192,808	N/A	Steel frame / curtain wall

Building Characteristics and Populations

Our process ensured 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. Commercial or residential usage and ranges for attributes such as footprint, frontage, depth, and number of floors were assigned to each building type, such that all buildings in PLUTO could be allocated among 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. We used PLUTO data fields for the principle building to determine the building type. This allowed us to assign each lot to one of the eight building types. Total citywide floor areas corresponding to each type were obtained by summing total floor area for each lot in each category and the results are summarized in Table 2.

Smaller residential buildings were classified as row houses if reported as attached or semi-attached in PLUTO, and as 1-2 family houses or residential low-rise (based on floor area) if detached. No information was available regarding building construction type, so we used "year built" as a proxy. For the residential sector, the more modern window wall architecture was assigned to buildings with 12 or more floors constructed in 2000 or later, with all other residential high-rise buildings taken as 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. Clearly this is a surrogate since curtain wall construction has been in use since the 1960s, and LiDAR and satellite imagery will allow more precise allocation to building types in future work.

Table 2. Criteria for classification of citywide building floor area

Type	Stories	Floor area above ground (sf)	Period	Buildings	Citywide floor area	
					Fraction	10^6 sf
1-2 Family house	1-3	<3001	All	340,273	14.6%	460
Row house	1-4	<5001	All	389,887	8.6%	777
Low-rise residential	1-7 (excluding 1-2 Family and Row House)		All	170,714	27.4%	1,461
Masonry high-rise residential	8-150	N/A	1700-1999	6,363	14.7%	782
	8-12	N/A	2000-2010			
Window wall high-rise residential	13-150	N/A	2000-2010	388	1.4%	72
Low-rise commercial	1-7	N/A	All	69,352	19.7%	1,052
Masonry high-rise commercial	8-150	N/A	1700-1999	2,941	12.6%	674
Curtain wall high-rise commercial	8-150	N/A	2000-2010	271	1.0%	52

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.

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, to ensure that all rooms in residential buildings had windows.

Building Simulation

The construction techniques modeled in each building type were typical for such buildings, but were adjusted to calibrate energy use to 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. Based on a study performed for Con Edison (Global Energy Partners 2010), residential lighting was mostly incandescent, while commercial lighting was all fluorescent. Residential lighting is now changing rapidly as a result of new federal regulations.

Table 3. Energy characteristics of building models

Type	Glazed fraction	AC type	Plug loads	Main fuel types[a]	Source EUI
			W/sf		kBtu/sf
1-2 Family House	15%	Window	0.7	#2 Oil, Gas, Electric	153
Row House	30%	Window	0.6	#2 Oil, Gas, Electric	144
Low-Rise Residential	30%	Window	0.6	Gas, #2 Oil, #6 Oil, #4 Oil, Electric	136
Masonry High-Rise Residential	30%	Window	0.7	Gas, #6 Oil, Steam, #4 Oil, #2 Oil, Electric	113
Window Wall High-Rise Residential	50%	PTAC	0.7	Electric, Gas	136
Low-Rise Commercial	30%	Rooftop	1	Gas, #2 Oil, Steam, Electric, #4 Oil, #6 Oil	290
Masonry High-Rise Commercial	30%	Central	1.3	Gas, #6 Oil, Steam, #2 Oil, #4 Oil, Electric	217
Curtain Wall High-Rise Commercial	60%	Central	1.3	Gas	222

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

Energy Use

Every building consumes energy for heat, hot water, building services such as 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, and federal studies of energy use in buildings (US DOE 2011; US EIA 2009).

Each building type may have its heat and hot water needs served by one or more fuels, 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.

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 for 2010.

Emission Summation

The fuel and electricity use for each building model was then scaled up using the ratio of all the floor area in the city corresponding to that type of building (Table 2) to the floor area in that building model (Table 1). 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, 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 while making adjustments to building characteristics such as infiltration, insulation, and the efficiency of the fuel-using equipment. Calculated fuel, electric use, and emissions for the entire city agreed with those in the Inventory to 1% or less.

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 increases in population and employment to estimate total future building floor area corresponding to each of our eight models, so that our results for each model could be scaled up to floor areas in the 2050 city. Second, we applied a wide variety of energy efficiency technologies to minimize their energy use and to switch to all-electric provisioning of remaining services.

Since 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 building was constructed 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.

The New York Metropolitan Transportation Council (NYMTC 2011) provided population and employment forecasts to 2040. They project that the population will grow 14% from 8,180,000 to 9,350,000, and that employment will climb 29% from 4,610,000 to 5,940,000.

Following a suggestion from the NYC Department of City Planning, population and employment values were kept constant from 2040 to 2050, since it is unclear that linear growth can be sustained within the city's spatial constraints.

Population information was used to determine the 2050 residential building floor area. From 2010 PLUTO data, we calculated a residential floor area density of 434 sf /person. Rather than resolve conflicting trends toward greater or less floor area per capita, this value was kept constant and used to provide an estimate for the total residential building floor 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. Consequently, the citywide floor 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. An argument could be made that there will be more growth in taller buildings and less in 1-2 family houses, but over a 35 year future, zoning requirements and real estate values are essentially unknowable, so we used the simplest available assumption.

The employment forecast of 29% growth was used to determine the commercial building area most likely to be present in 2050. From PLUTO data, we calculated a commercial floor area employment density of 386 sf /employee. This value was decreased by 1% every five years, as shifting job categories and economic pressure result in smaller workspaces. This generates a 19% increase in commercial building area by 2050, the same for each building type.

Building Sector Energy Reduction Measures and Savings

Reductions of energy use in and emissions from buildings are achieved by a series of energy efficiency measures, consisting of air sealing to 0.2 ACH at natural conditions, energy recovery ventilation, lower vision glass to a maximum of 50% window-to-wall ratio, insulation increased to R-20 or R-30 on walls and R-50 on roofs, triple glazing, sunshades for south windows, air-source heat pumps for domestic hot water, heat recovery on heat pumps for cooling season domestic hot water (DHW), induction cook stoves, heat pump laundry dryers, and the most efficient appliances available today. We employed mini-split air source heat pumps for most residential HVAC and ground source heat pumps for high-rise masonry residential and all commercial buildings. The impact of the measures was estimated applying these measures to the 2010 eQUEST models described previously.

Our analysis assumed no significant lifestyle changes. 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 used only standard clock-driven setbacks. All the technologies are available today, although some are not yet common.

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 infiltration of 0.4 ACH and about 30% less additional insulation.

Cost Estimates

In order to get a sense of the economic feasibility of enacting the measures described above, the cost-estimating group of Lend Lease (US) Construction LMB, Inc. provided us with 2012 estimates of the cost of each retrofit or improvement in each building. They are available on a per square foot, per dwelling unit, and per building basis (UGC 2013b), and are summarized in Table 5 for each building type. 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 those savings might offset.

Two types of measures are used in our analysis. The first type is one that would be done only for its energy value, and not in the course of normal building maintenance. Adding insulation and carrying out air sealing are two examples of this type, and for these, 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. Many items wear out and must be replaced, especially over a 35 year time horizon. For these measures, we included only the incremental cost above that of a standard item. For example, for the cost of triple-glazed fenestration, windows in existing buildings will require replacement, and new buildings will require windows, so we count as the “cost of the measure” only the incremental cost above the normal double-glazed item. Key building components that will be replaced or undergo major rehabilitation include windows, window walls, curtain walls, boilers, burners, HVAC controls, PTACs, air conditioners and DHW equipment.

Results

Final Building Electricity Requirements

The building models were run again with the measures of section 2.3 implemented, and the resulting electric use and EUIs are presented in Table 4. Here, the total electric energy consumed in each modeled building type is shown in column 2. 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, column 3 of Table 4 shows 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.

However, if the electricity in 2050 is carbon-free, site energy and source energy are equivalent, and give rise to the final EUIs in column 4 of Table 4.

Table 4. Electric use and source energy use intensities in 2050 buildings

Building Type	Building Energy Usage			Impact of Photovoltaics If Used[a]	
	Total Electric	2050/2010 EUI[b]	2050/2050 EUI[c]	PV Production	Net Electric Use
	MWh/yr	kBtu/sf	kBtu/sf	MWh/yr	MWh/yr
1-2 Family House	9.0	64	23	7.2	1.8
Row House	14.5	70	25	8.4	6.1
Low-Rise Residential	61.4	70	25	27.5	33.9
Masonry High-Rise Residential	580	45	16	80	500
Window Wall High-Rise Residential	1,020	53	19	72	948
Low-Rise Commercial	195	123	44	100	95
Masonry High-Rise Commercial	2,100	87	31	180	1,920
Curtain Wall High-Rise Commercial	1,760	87	31	120	1,640

[a] Photovoltaics added to 50% of buildings citywide

[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.

Rooftop Photovoltaic Collectors

The average solar insolation in NYC is 4.34 kWh/m^2 per day for a flat solar panel tilted at an angle equal to latitude. Photovoltaic (PV) panels were added to the rooftops of each of our building models for 2050, with panel efficiencies of 20%. As solar panels produce direct current (DC) power, an inverter was required, at a conversion efficiency of 90%.

Photovoltaic panels were added to the rooftops of our models, but in order to leave room for fire lanes, elevator houses, and other items, they were added covering only 50% of the footprint area of each building. (The footprint can be derived from Table 1 by dividing area by stories.) Each PV model was allowed unshadowed access to the solar resource, and the resulting generation for each building type is shown in Table 4. However, there will be shadowing and other obstructions, so we assumed that only half the actual buildings of each type had access to sunshine, and collectors were only added to one-half of the roofs. This reduced the scaling factor by 50%, and the net energy added to the grid (below) from onsite rooftop PVs included this reduction. The resulting city-wide generation is about 25% greater than that found by the New York City Solar Map (http://nycsolarmap.com, accessed October, 2012.) because our collectors were assumed more efficient than the standard 2010 devices they modeled.

Electric Generation Needed

When the electric energy needed to power the buildings was summed across building sectors, the total requirement to maintain the city's buildings for one year was 50.6 terawatt-hours (TWh), about equal to the 2010 consumption of 49.5 TWh. On-site PV production produced 10.7 TWh in our scenario, reducing net building electric energy use to 39.9 TWh.

In the second, less rigorous scenario for our building energy reduction measures described in Section 2.3, 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 indicates that we may be able to tolerate a less rigorous program of building improvement than our base case.

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 (Fthenakis et al. 2009; Jacobson and Delucchi 2011) and for New York State (Jacobson et al. 2013). Here, NYC buildings will need 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, Canadian hydro, PV arrays on roads, parking lots, and other open space and/or up to three nuclear generation stations. We 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 temporal matches between load and supply present separate challenges. eQUEST calculates the peak electric demand 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%, defined as the ratio equal to the scaled sum of the modeled 2010 building demands divided by the summertime, air-conditioning-driven building peak load of 7,960 MW in 2010 reported by Con Edison (NY ISO 2012). The result is a winter, night, space heat-driven peak building load of 12,600 MW in 2050, a 58% increase over total 2010 building load. This result is not surprising, since heat pumps generate a peaked load like air conditioners, but based on heating loads rather than cooling.

It is clear that a substantial increase in distribution capacity will be needed, as will a considerable amount of storage capability. The storage will have to match the daytime 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.

Cost Estimates for Building Improvements

The cost estimates discussed earlier are summarized in Table 5 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 costs averaged over each building class.

Table 5. Costs of proposed retrofit measures

Building Type	Incremental Retrofit Cost	Cost/Unit	Cost/m^2	Cost/sf
1-2 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	-	$394	$36.58
Masonry High-Rise Commercial	$6,970,000	-	$327	$30.41
Curtain Wall High-Rise Commercial	$11,180,000	-	$624	$58.00

The cost estimates were scaled up to develop an estimate of the total cost of retrofitting NYC. 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, about 7% of the city's municipal budget or 0.4% of the gross municipal product. It also corresponds to an investment of about $585 per year for each of 8.2 million New Yorkers now in residence. The capital outlays have a net present value of $94 billion in 2012 when discounted at 3% per year in constant dollars (Fuller and Petersen 1996).

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. To develop 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), shown in Table 6. We found that a reduction in commodity costs of 1.5 percent per year would reproduce this reduction over 35 years, and ascribed each annual reduction (of 1.5%) to the capital investment made the year before. We assumed that each investment would continue to produce savings for 30 years. The result was a net present value of the savings over the 35 year period of $87 billion in 2012, again using a 3% per year constant dollar discount rate. These savings are 93% of the total discounted capital cost.

Table 6. 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

So under our baseline assumptions, the measures described above come very close to paying for themselves, using long-term economic methods. 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.

Any realistic scenario for the future will violate our baseline assumptions in four ways: fuel prices will rise faster than inflation, the costs of our proposed measures will fall as they become standard practice, inclusion of our measures in new construction will be less costly than implementing them as retrofits, and substantial fiscal benefits will accrue from the dramatic decline in air pollution (Jacobson et al. 2013). Under any plausible mix of these factors, the measures taken citywide will be either cost neutral or a net economic gain.

There is no question that the total costs are intimidating. However, the potential costs of not acting will become ever more clear, and may shift current attitudes dramatically. Current estimates of the cost of the damage from hurricane Sandy are in excess of $65 billion, 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 energy savings near the cost of proposed changes, carrying out 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 2012). 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 (UGC 2013b). 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 (BPI 2013; UGC 2013a).

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 conversion to all electric power from carbon-free sources more practical. 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 distribution system capacity 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 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.

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