Preparing for a City-Scale Building Energy Upgrade Analysis:

A Case Study for New York City

Preparing for a City-Scale Building Energy Upgrade Analysis:

A Case Study for New York City

PURPOSE

The New York City Mayor's Office of Sustainability requested technical assistance on building stock analysis from the U.S. Department of Energy (DOE), under the Community Data Analysis program.

The purpose of this document is to offer an overview of the value of detailed building stock energy-efficiency analysis and to provide actionable steps New York City (NYC) can take to prepare for such a study. There are a variety of approaches to building stock energy-efficiency analysis. This document focuses on the approach taken by the open-source ResStock™ and ComStock™ tools, because NYC is interested in learning how it can leverage DOE investment in this area.

Although this document was prepared specifically for use by NYC, and the examples highlight application in the NYC context, the steps are written to be generalizable so that other cities interested in building stock analysis can use this as a framework.

In this document, we overview the ResStock/ComStock approach to building stock analysis and recommend seven steps that cities can undertake to prepare to use these tools:

1. Develop target questions
2. Identify partners
3. Collect data
4. Establish scenarios
5. Define metrics
6. Plan a results presentation
7. Identify gaps.

In the next section, we introduce building stock analysis before defining each of the seven preparation steps in detail.

Illustration from iStock 1064365920

Introduction to Building Stock Analysis

Cities across the United States have shown increasing interest in developing policies around reduced greenhouse gas (GHG) emissions, energy efficiency, air quality, and sustainability. Buildings in the United States consume approximately 40% of all energy[1] and 75% of all electricity,[2] so any impactful GHG or energy goal needs to consider cost-effective efficiency improvements to the building sector. Physics-based building stock analysis has emerged as a popular tool in many areas for targeting reductions. The advantages of these models are that they provide bottom-up detail, often at the building level, they decompose loads to end uses (i.e., heating, cooling, lighting, water heating, and so on), and they link energy use to the physical processes that lead to demand. This makes it easy to quantify the energy benefits from efficiency upgrades or electrification of space and water heating.

The most common method of building stock analysis uses a prototype-based approach. In this approach, a model is developed that represents a whole segment of the building stock—for example, high-rise commercial office buildings built post-1980. Each model is built using a building modeling software to simulate energy use in that building type for a year. The prototypes are then scaled to the city level by mapping the number of actual buildings in the city that fall into each prototype category. The scaled results are then calibrated to energy consumption data. The building stock model can then provide present-day information on where energy is being consumed, but more usefully, it can be used in scenario analysis and development. For example, technologies in certain prototypes can be changed (e.g., installing air-source heat pumps in all residential buildings), and the impact on the energy consumption can be tabulated. The advantage of building stock analysis is the high spatial detail and the direct link to technology options.

When models are well calibrated to local data on energy and the building stock, the model outputs increase in accuracy and can be quite valuable for decision-making, even for questions that require detailed spatial or temporal resolution. The building stock analysis itself quantifies changes in energy consumption by end use and fuel type, but these model outputs can be easily joined with other parameters of interest that are correlated with energy consumption, such as cost and emissions. The quality of these linked outputs also depends on the quality of data on these topics for the local context.

1 https://www.eia.gov/tools/faqs/faq.php?id=86&t=1

2 https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_01

How to Prepare for a Detailed Building Stock Analysis

Building stock analysis can provide valuable, detailed insights into energy consumption and savings potential across a city, but the quality and ease with which such an analysis can be conducted is largely dependent upon appropriate framing of the project goals, engagement of relevant partners, and the quality of data inputs. In this section, we highlight the necessary steps that NYC can undertake to prepare for a building stock analysis.

1. **DEVELOP TARGET QUESTIONS.** The first step in preparing for a building stock analysis is to identify the target questions that the city wants answered through the building stock potential analysis. This step is critical, because the target questions for the project will inform which data are collected, how the analysis is performed, which scenarios are included, and which city stakeholders should be project partners. This step also includes identifying the audience for the analysis results—for example, NYC has identified five audiences for its analysis: building owners, contractors, utility companies, the New York City Mayor's Office of Sustainability, and other city agencies. Relevant to these audiences, key questions for a building energy-efficiency analysis could include:
   - **Building owners**
     - What building upgrades are cost-effective for my building?
     - How much can I save on operating costs?
   - **Contractors**
     - Which buildings are the best candidates for a specific technology or retrofit?
     - Where are these buildings located?
   - **Utility companies**
     - What would the impact be of building-efficiency policies and building retrofits on electric grid demand and system resilience?
     - What technology retrofits would have the largest impact on peak electricity demand?
     - Can energy efficiency and demand-side management offset projected electricity infrastructure upgrades (i.e., non-wires alternatives)?
     - Would disruptive technology change, such as electrification, require infrastructure upgrades, and where would those be needed?
   - **The New York City Mayor's Office of Sustainability**
     - What impact would different policies have on buildings across the city?
     - Which technology combinations would be most cost-effective for helping meet NYC carbon and air quality goals?
     - How would technology upgrades in buildings impact local air quality?
   - **Other city agencies**
     - How much potential is there for energy reduction through retrofits in city-owned buildings?
     - Which buildings should be prioritized first?
2. **IDENTIFY PARTNERS.** Once key questions have been defined, potential partners should be identified to lead or assist with the effort, such as local firms, utility companies, and nonprofit organizations that are intimately familiar with the city's building stock and the retrofits commonly implemented. These organizations can help collect necessary data, ensuring that the local context is appropriately captured in the model, validate analysis results, help implement actions recommended from modeling, and improve the visibility of the project to the local community. Identifying the appropriate partners is key to project success. In the case of NYC, local partners are well known, because the city has engaged extensively with a Buildings Technical Working Group containing leaders from a variety of organizations, including real estate, engineering, architecture, labor unions, affordable housing advocates, academic institutions, governments, and environmental advocates. This group produced a report on local building characteristics and common retrofits for buildings greater than 50,000 square feet.[3] This type of partner organizational information will be invaluable for developing the project.
3. **COLLECT DATA.** Collecting the appropriate data is one of the most critical and potentially time-consuming portions of preparing for a building stock analysis. Stock models typically have default parameters based on nonlocal characteristics. In the case of ResStock/ComStock, these

3 https://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/TWGreport_04212016.pdf

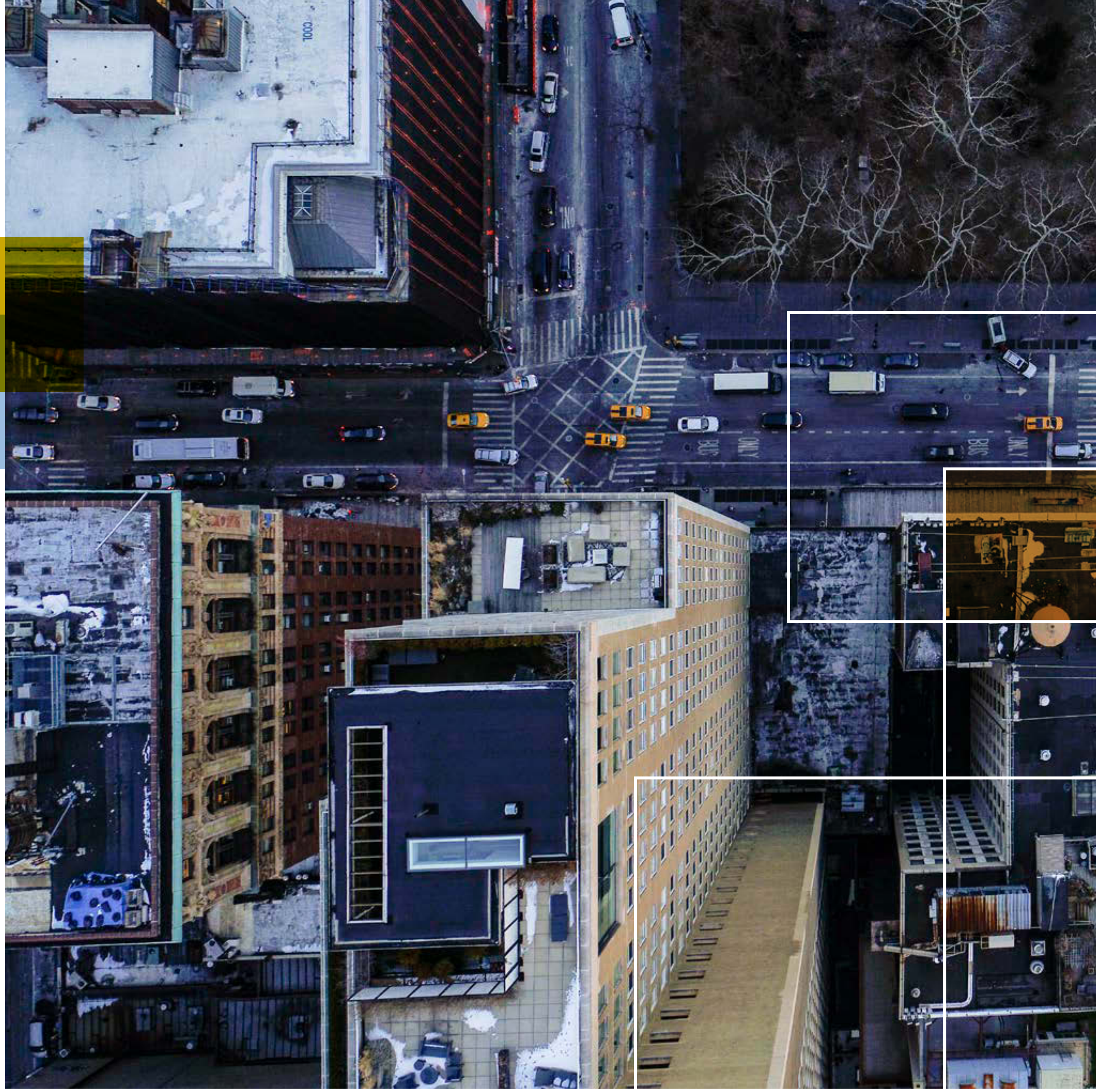


Photo from iStock 952680040

parameters are based on national surveys of building stock characteristics and energy consumption. However, incorporating local context will improve the accuracy of the models, and local data should be used whenever possible. For example, national surveys might find that most buildings of a category use a certain type of wall construction with associated thermal properties, but local construction assemblies could vary significantly from these "typical" national cases and have impacts on energy use and recommended savings opportunities. In general, there are five categories of data that cities should compile to prepare for a building energy-efficiency stock analysis:

- **Building type and location.** To be able to map the results study, the building stock model needs a spatially explicit accounting of where buildings are in the city and the classification of the building. These data are typically obtained from a county assessor database, which generally includes addresses and classifications, or from a geographic information system (GIS) database, which can provide latitude and longitude coordinates. In the case of NYC, DOE has already generated unique building identifications,[4,5] for all of the buildings in the city, which could be used in georeferencing results back to city geography.

4 https://buildingid.pnnl.gov/

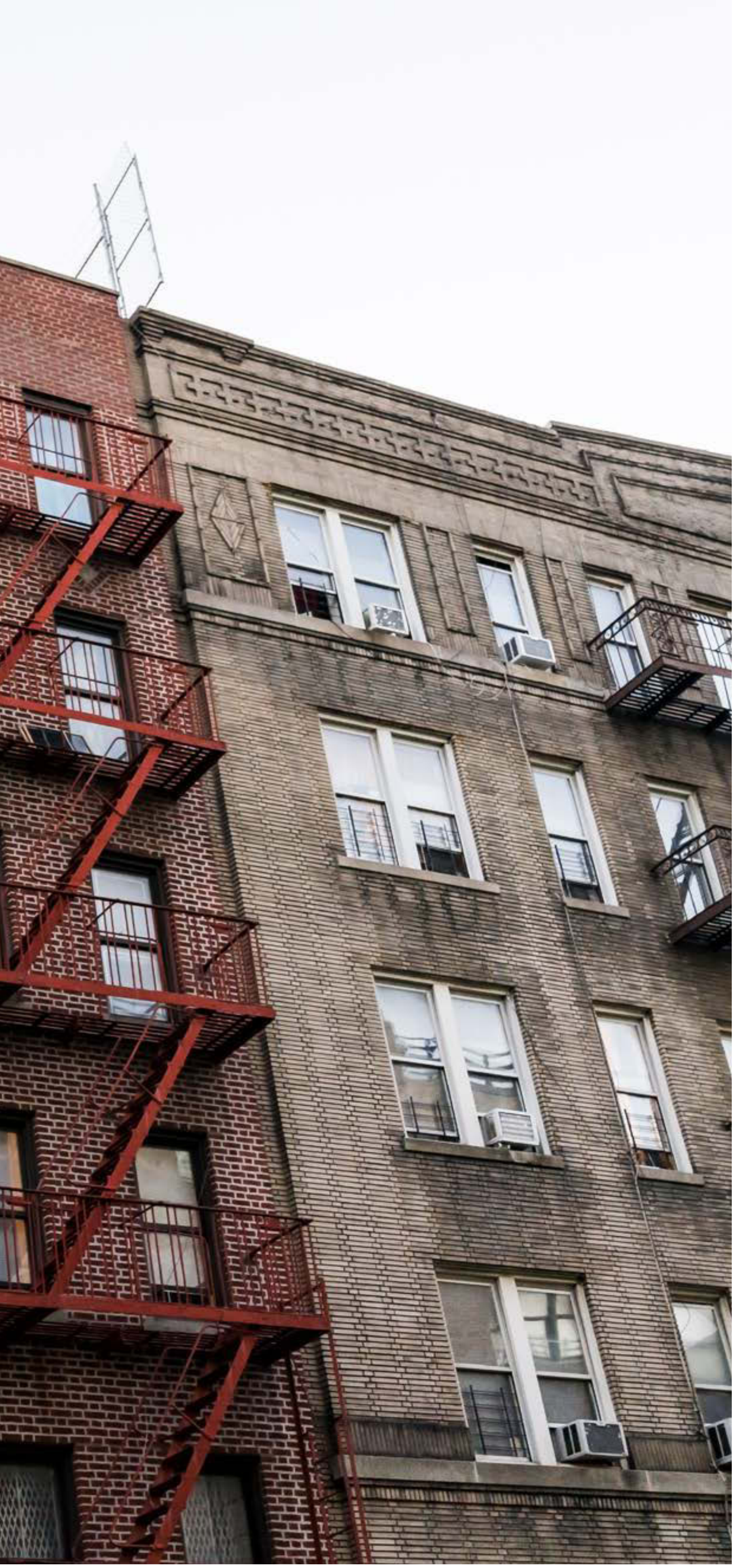
5 https://buildingid.pnnl.gov/pdf/UBID_Year_in_Review_Final_265829.pdf

- **Building stock geometry** (shape, number of stories, floor area). Building stock models segment the building population into subsets and develop three-dimensional physical models of representative buildings in each category. Having realistic geometry on the shape and size of these buildings is important for developing these models; building shapes can also vary greatly region to region. For example, a western city might have single-story ranch-style homes for most of the residential stock. In the case of NYC, these could be multistory attached homes or high-rise buildings. Data on the geometry of buildings might already be collected by city planning agencies or the county assessor's offices, or samples of geometry might be available through audit disclosure. If these sources are lacking, especially in variables such as the number of building stories, the Residential Energy Consumption Survey,[6] or the Commercial Buildings Energy Consumption Survey[7] from the U.S. Energy Information Administration (EIA) can also provide regional data to supplement building geometry data. The format of these data could be two-dimensional or three-dimensional GIS files, tabulated floor area in a database, or other qualitative descriptors of building geometry. Some cities also have access to remotely sensed data (e.g., lidar, Google Street View, or satellite images), and they are viable data sources for geometry, but they do require substantial processing to extract the relevant information on building geometry.
- **Building stock characteristics** (building materials, appliances, and fuel supply). To complement the information on the physical shape of the buildings, each of the prototype models needs data on the type of materials used to construct the building, the energy-consuming appliances and equipment within the building, and the fuel type supplying each of these devices. Because these characteristics are not externally visible to the building, these data might be less readily available, and the models might have to rely upon more sample and survey data. This is especially true for characteristics such as building wall assemblies. Potential data sources for these data include audit results, building permits, county assessor databases, and surveys (EIA or local). Real estate databases (e.g., CoStar for commercial) might also be useful for supplementing equipment information found in an assessor database.

Photo from iStock, 909378158

6 https://www.eia.gov/consumption/residential/

7 https://www.eia.gov/consumption/commercial/



- **Energy consumption** (electricity, natural gas, steam, and other fuels). Information on the energy consumption will be used to calibrate the building stock model. Often, monthly utility bills for a subset of buildings can be used in this capacity, but there are some applications for which monthly bills will be insufficient. For example, to analyze energy-efficiency retrofits that might offset peak electrical demand, having more detailed hourly or 15-minute data interval information will be necessary. Any other data on building use behavior (e.g., occupancy schedules, internal temperature setpoints, and so on) are also useful supplements for model calibration. Potential sources of data on consumption include monthly bills, energy disclosures, advanced metering infrastructure (i.e., smart meters) data, and surveys.
- **Cost** (energy and purchase/labor). Cost data are not strictly required to calibrate and run a building stock assessment; however, many target questions in the energy-efficiency analysis will include elements of cost-effectiveness, so we consider good cost data as essential for most analyses. Relevant cost information for an analysis includes:
    - Local equipment purchase and installation prices. Consult local installers, utility programs, RSMeans data (apply relevant location factors), or the National Residential Efficiency Measures Database.[8]
    - Electricity tariffs and rates for natural gas, fuel oil, and propane. ResStock and ComStock can calculate customer utility bills using electricity tariff information in the U.S. Utility Rate Database.[9] Future or hypothetical utility rates can be specified using the U.S. Utility Rate Database format. Rates for natural gas, fuel oil, and propane can be determined from EIA data.[10]
    - Local rebates and incentives. Consult utility programs or the Database of State Incentives for Renewables & Efficiency™.[11]

8 https://remdb.nrel.gov/

9 Visit https://openei.org/wiki/Utility_Rate_Database to find up-to-date rates for the top 150 utility companies representing 70% of U.S. electricity sales; rates for smaller companies can be submitted by volunteers.

10 Natural gas prices by sector and state can be found here: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm. Heating oil and propane by sector by state can be found here: https://www.eia.gov/petroleum/heatingoilpropane/.

11 http://www.dsireusa.org/

Table 1. Available Data Sources for Building Stock Analysis in New York City

Data Type	New York City Example	Parameters of Interest
Building Specific or Parcel		
Assessor data	Primary Land Use Tax Lot Output database https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-pluto-mappluto.page	Building class, residential/commercial area breakdown, number of buildings, number of floors, and year built
Permit data	NYC-DOB Permit Issuance https://data.cityofnewyork.us/Housing-Development/DOB-Permit-Issuance/ipu4-2q9a	Residential, permit type, building type, and date
Permit data	CATS Permits (boiler and industrial operations) https://data.cityofnewyork.us/Environment/CATS-Permits/f4rp-2kvy	Address, building identification number, primary and secondary fuel type, make, and model
Energy use	NYC Housing Authority (NYCHA): Electric Consumption and Cost https://data.cityofnewyork.us/Housing-Development/Electric-Consumption-And-Cost-2010-2017-/jr24-e7cr	Consumption (kilowatt-hours), service start date, and service end date
Energy use	NYCHA: Water Consumption and Cost https://data.cityofnewyork.us/Housing-Development/Water-Consumption-And-Cost-2013-2017-/66be-66yr	Consumption (hundred cubic feet), service start date, and service end date
Energy use	NYCHA: Heating Gas Consumption and Cost https://data.cityofnewyork.us/Housing-Development/Heating-Gas-Consumption-And-Cost-2010-2017-/it56-eyq4	Consumption (thermal units), service start date, and service end date
Energy use	NYCHA: Cooking Gas Consumption and Cost https://data.cityofnewyork.us/Housing-Development/Cooking-Gas-Consumption-And-Cost-2010-2017-/avhb-5jhc	Consumption (thermal units), service start date, and service end date
Energy use	NYC Energy Benchmarking Report 2010–2017 https://www1.nyc.gov/site/finance/taxes/property-reports/nyc-energy-benchmarking-report.page	Building identification number, borough, block, lot, ENERGY STAR® score, end use intensity, and greenhouse gas emissions
GIS	OpenStreetMap https://www.openstreetmap.org/#map=4/38.01/-95.84	Building footprints
Energy audit	Local Law 87 Energy Audit and Retro-Commissioning data (internal NYC) https://www1.nyc.gov/site/buildings/business/energy-audits-and-retro-commissioning.page	Building identification number, building geometry and makeup, energy conservations measures, and building construction and systems

Data Type	New York City Example	Parameters of Interest
Boiler permit data	CATS Permits https://data.cityofnewyork.us/Environment/CATS-Permits/f4rp-2kvy	Address, building identification number, borough, block, lot, make, model, fuel, and issue date
Tax map	NYC-Department of Finance Digital Tax Map http://gis.nyc.gov/taxmap/map.htm	Map of parcels, number of floors, year built, and number of residential units, number of commercial units
Sales	NYC-Department of Finance Rolling Sales https://www1.nyc.gov/site/finance/taxes/property-rolling-sales-data.page	Number of residential units, number of commercial units, ZIP code, and gross square feet
Tools	Geographic Online Address Translator http://a030-goat.nyc.gov/goat/Default.aspx	Building identification number, address, latitude and longitude, building class, census tract/block, and vacant lot
Census Block/Tract		
Demographics	American Community Survey https://www.census.gov/programs-surveys/acs/	Heating fuel type, number of units, renter versus owner occupied, vintage, and number of rooms
Demographics	U.S. Census Bureau https://www.census.gov/data.html	Total population, rented versus owned units, and number of people in household
Survey	Residential Energy Consumption Survey https://www.eia.gov/consumption/residential/index.php	Housing characteristics and consumption and expenditures
Borough/County		
Survey	New York Residential Statewide Baseline Study (NY RSBS) Single and Multifamily Occupant Survey: Part 1 https://data.ny.gov/Energy-Environment/RSBS-MOM-Part-1-of-2-New-York-State-Residential-St/e58s-chjh	Heating, ventilating, and air conditioning; fuel types; and appliances
Survey	NY RSBS Single and Multifamily Occupant Survey: Part 2 https://data.ny.gov/Energy-Environment/RSBS-SMO-Part-2-of-2-New-York-State-Residential-St/87mp-9bnv	Appliances and lighting
Survey	NY RSBS: Single Family On-Site Inspections, Measures Level https://data.ny.gov/Energy-Environment/RSBS-Single-Family-On-Site-Inspections-Measure-Lev/c8sd-bzeb/data	Appliances; heating, ventilating, and air conditioning; lighting; plug loads; and envelope
Survey	NY RSBS: Single Family On-Site Inspections, Site Level https://data.ny.gov/Energy-Environment/RSBS-Single-Family-On-Site-Inspections-Site-Level-/8wa7-87p5	Air leakage, foundation type, roofing, siding, window shading, and garage

Beyond the core five areas of data for stock assessment, there might be other necessary data depending on the target questions for the study. For example, studying the impact of efficiency on low-income or minority communities might be a portion of the study, so relevant demographic data might need to be compiled. These might be available through city agencies or the U.S. Census Bureau, which provides spatially detailed demographic information. Other possible data for assessment include the photovoltaic solar energy generation potential or the presence of district heating and cooling systems. If the analysis requires substantial future projections, additional information on population trends, building stock growth, or planned new developments should be included.

Beyond locating all of the data sources listed above in support of the target questions, the city should also work to validate and clean the data sources and cross-reference them to one another. When possible, all data should be linked back to the building level (or each building should be linked to relevant aggregated data for its location, e.g., census block income level). Any differences in information from different data sources should be reconciled. City staff can work with the National Renewable Energy Laboratory (NREL) or trained consultants to format the data and ensure that the necessary parameters in support of the building stock analysis have been located. In the case of NYC, the city has already invested substantial time and effort in collecting building data. Many of these data are public and already easily accessible. There are also several in-process efforts in NYC that might ease data collection and processing. For example, starting in 2019, all of the large commercial buildings undergoing annual audits as required by Local Law 87 will be required to use DOE's Audit Template and Asset Score, which will automatically create BuildingSync® common schema output[12] and export it to NYC's Standard Energy Efficiency Data (SEED) platform.[13] Audit data for previous years are also being converted to BuildingSync. These data will be readily accessible and ready for stock modeling via SEED. A similar potential requirement of including a Home Energy Score[14] and data output into Home Performance Extensible Markup Language (HPXML)[15] at the point of listing for sale could likewise standardize residential data. A table of known NYC data for stock modeling is provided in Table 1.

4. **ESTABLISH SCENARIOS.** Once target questions, partners, and data sources have been identified, the city should map which sectors, technologies, or policy scenarios should be analyzed to answer the target questions. The scenario development should put specific technologies and years to the target questions. For example, to study pathways for reaching city 80-by-50 GHG goals, specific scenarios could be developed to examine the potential for air-source mini-split heat pumps in certain types of buildings to reduce emissions. Similarly, scenarios around aggressive electrification of space and water heating could be developed to look at emissions impacts, costs, and electric system impacts. Scenarios could also be specifically geographically tagged so that the local impacts of different scenarios could be identified. This type of spatial resolution is especially important for analyzing health impacts from air quality improvements. The scenarios should be as specific as possible with regard to the technologies and sectors included, but a building energy-efficiency analysis framework gives the capability of running a variety of scenarios and comparing the results to identify the most appropriate pathways, as defined by the city goals and priorities.

5. **DEFINE METRICS.** For each of the scenarios, the city should define appropriate metrics for evaluation. The metrics and scenarios should be defined in a way that the outcomes of the modeling will answer the key target questions defined in Step 1. These metrics will likely focus on cost-effectiveness (for different stakeholders), energy savings, and other health or environmental indicators. Potential metrics for NYC include:

   - **Energy**
     - Site energy savings by fuel type (fuel oil No. 2, fuel oil No. 4, natural gas, district steam, and electricity)
     - Source energy savings by fuel type (fuel oil No. 2, fuel oil No. 4, natural gas, district steam, and electricity)
   - **Cost/economic**
     - Customer utility bill savings
     - Customer operation/maintenance savings
     - Customer return on investment for retrofits
     - Utility operational savings

12 https://buildingsync.net/

13 https://www.energy.gov/eere/buildings/standard-energy-efficiency-data-platform

14 https://betterbuildingsinitiative.energy.gov/home-energy-score

15 http://www.hpxmlonline.com

- Utility capital expenditure savings
- Property value increase/tax revenue
- Sales revenue for local businesses
- Jobs created
- Cost savings for vulnerable populations (geographically tagged)

• **Environmental**
  - Avoided GHG (average and marginal savings)
  - Avoided criteria air pollutants (e.g., fine particulate matter, sulfur oxides, and nitrogen oxides)
  - Societal cost/benefit ratio, including health and air quality benefits
  - Reduction in exposure for vulnerable populations (geographically tagged).

6. **PLAN A RESULTS PRESENTATION.** In preparing for a building energy-efficiency analysis, the city should determine the final presentation of results that would be most useful for implementation, including both visualization and resolution of the results. The visualization could include geospatial maps of savings, time-series electric load results, time-series emission levels, or other types of graphs. The city should also prepare any necessary data to supplement for visualization (e.g., GIS information on buildings or grid components not included for the core model development).
7. **IDENTIFY GAPS.** As a final step in preparing for a building stock energy-efficiency analysis, the city should work with NREL to identify any gaps in NREL's stock modeling capabilities that will be necessary to update for the desired scenarios and outcomes. Examples include city-specific technologies, such as steam boilers or district energy systems, that might not be well represented in current models. This could also include desired outcome indicators, such as location-tagged criteria air pollutants or specific cost/performance indicators. The city and NREL will jointly create a plan for addressing the gaps and upgrading modeling capabilities.

Overview of ResStock and ComStock Capabilities

Existing Building Stock Analyses in NYC

To our knowledge, there are two major existing academic studies on disaggregated building stock energy use in NYC. However, neither of these is as comprehensive as the approach to building stock analysis presented in this case study. One study, performed by Howard et al. at Columbia University in 2012, estimated end-use energy consumption at the tax lot level by statistically decomposing ZIP-code-level electricity and fuel consumption.[16] This project also produced an interactive online map for public exploration.[17] A limitation of this model is that it does not link energy consumption to specific appliances and physical processes in the building, so it is more difficult to evaluate retrofit strategies.

The second study was performed by Li et al. at Georgia Institute of Technology in 2015.[18] For this study, the authors used reduced order modeling, based on simple regression models, for all of the buildings in Manhattan only. For commercial buildings, the authors derived reduced order models using DOE prototypical models for 16 commercial building types (based on data representing the entire United States) and developed their own residential building models. There are some similarities between this model and the approach presented in this case study, but it lacks the same level of accuracy because of: (1) the use of relatively few prototype models that lack diversity in characteristics, (2) the use of national prototypes to represent the NYC context, and (3) the simplified thermal building modeling. The focus of this study was also more on studying the urban heat island effect and less on energy-efficiency potential. The model in this case is not public, so the applicability of the findings is limited, because not many scenarios were analyzed.

Tools for Building Stock Analysis

In the U.S., advanced tools have emerged for building stock analysis using several different approaches. Some building stock models are population models, meaning that every single building within a building population has a unique

16 Howard, B., L. Parshall, J. Thompson, S. Hammer, J. Dickinson, and V. Modi. 2012. "Spatial distribution of urban building energy consumption by end use." *Energy and Buildings* 45: 141–151. doi: 10.1016/j.enbuild.2011.10.061.

17 http://qsel.columbia.edu/nycenergy/

18 Li, Q., S.J. Quan, G. Augenbroe, P. P.-J. Yang, and J. Brown. 2015. "Building Energy Modelling at Urban Scale: Integration of Reduced Order Energy Model with Geographical Information." Proceedings of the *Building Simulation 2015: 14th Conference of International Building Performance Simulation Association*. 190–198.

building energy model with accurate geometry. Examples of population models include AutoBEM[19], CityBES[20], and UMI[21]. These types of models are excellent for the modeling of smaller campuses or neighborhoods when large amounts of data are available on the buildings. Population models can also be highly useful when designing a neighborhood and to optimize energy interactions between buildings. For example, URBANopt[22] was used to study interactions between building loads, distributed energy resources, and the electric distribution system for a new commercial district in Denver.[23] The major drawback of the population approach for large cities is the time and data necessary to develop these models. Even if energy consumption data are available to calibrate building energy use on a building-by-building basis, models may be calibrated inappropriately due to lack of sufficient data on physical building characteristics or occupant behavior. For larger geographical areas, statistical modeling approaches are generally more appropriate, as they inherently account for the modeling uncertainty around building characteristics and occupant behavior for each specific building within the stock.

An Introduction to ResStock and ComStock

NYC is interested in a number of analysis questions that would benefit from a statistical approach to building stock analysis that uses a higher degree of granularity in capturing the diversity of building stock characteristics. NREL has developed state-of-the-art building stock analysis tools for DOE: ResStock is used to analyze national, regional, and local residential building stocks, and the forthcoming ComStock capabilities will enable commercial building stock analysis at various scales.[24] These free, open-source tools utilize DOE's best-in-class energy modeling simulation engine, EnergyPlus™.[25] In their basic configurations, ResStock and ComStock leverage publicly available data—such as national building surveys and census data, combined with a few proprietary data sets—to model the entire U.S. building stock.

ResStock and ComStock use prototypes to represent segments of the building stock, but one aspect that distinguishes these tools from other stock models is the level of spatial granularity and heterogeneity of modeled building stock characteristics, which provide more accurate results. Most traditional building stock analyses use a single simulation model to represent a segment of the building stock. For example, a single simulation that represents all single-family homes built between 1950 and 1960, using typical building characteristics, would be used to estimate typical energy consumption and savings potential. In practice, this does not capture the true range of energy consumption across the entire segment of the building stock. Continuing the fictional example of the 1950s residential prototype, assume 59% of the buildings in that category use natural gas water heating and 41% use electric water heating. In the traditional building stock analysis approach, all buildings in that category would be represented by a model using natural gas water heating, neglecting the significant portion of the buildings that use electric water heating, thus skewing the fuel type split.

In contrast to these traditional building stock analyses, ResStock and ComStock utilize weighted distributions of many hundreds or thousands of models to represent a single building type or vintage. The distributions include dependencies between parameters to account for their relationships to one another (e.g., building age and insulation levels). Figure 1 illustrates the structure of parameter dependencies typically used to represent the residential building stock. This approach is able to model the full diversity of building appliances and thermal characteristics that exist.

19 New, Joshua, Mark Adams, Piljae Im, Hsuihan Lexie Yang, Joshua Hambrick, William Copeland, Lilian Bruce, and James A Ingraham. 2018. "Automatic Building Energy Model Creation (AutoBEM) for Urban-Scale Energy Modeling and Assessment of Value Propositions for Electric Utilities." In *Proceedings of the International Conference on Energy Engineering and Smart Grids (ESG)*.

20 https://citybes.lbl.gov/

21 http://web.mit.edu/sustainabledesignlab/projects/umi/index.html

22 https://www.nrel.gov/buildings/urbanopt.html

23 https://www.nrel.gov/news/press/2017/nrel-announces-partnership-with-panasonic-and-xcel-energy.html

24 https://resstock.nrel.gov

25 https://www.energy.gov/eere/buildings/downloads/energyplus-0

The use of many thousands of representative building models leads to more resolute results, but it also requires many more simulations and more computational power. The Amazon Elastic Compute Cloud is typically used to quickly and cheaply run all of the necessary simulations, though the simulations can also be configured to run on NREL's supercomputer.

Figure 2 illustrates how the high-granularity approach taken by ResStock/ComStock enables more accurate estimates of savings potential by targeting specific housing stock segments with particular efficiency measures.

Outputs from previous applications of ResStock include technical potential (savings from full stock retrofits) and economic potential (cost-effective savings[26]) of different technologies by identifying which types of buildings have the most potential and where they are geographically located, segmented by fuel type. This implementation of the model has been used to produce state-level fact sheets for the residential

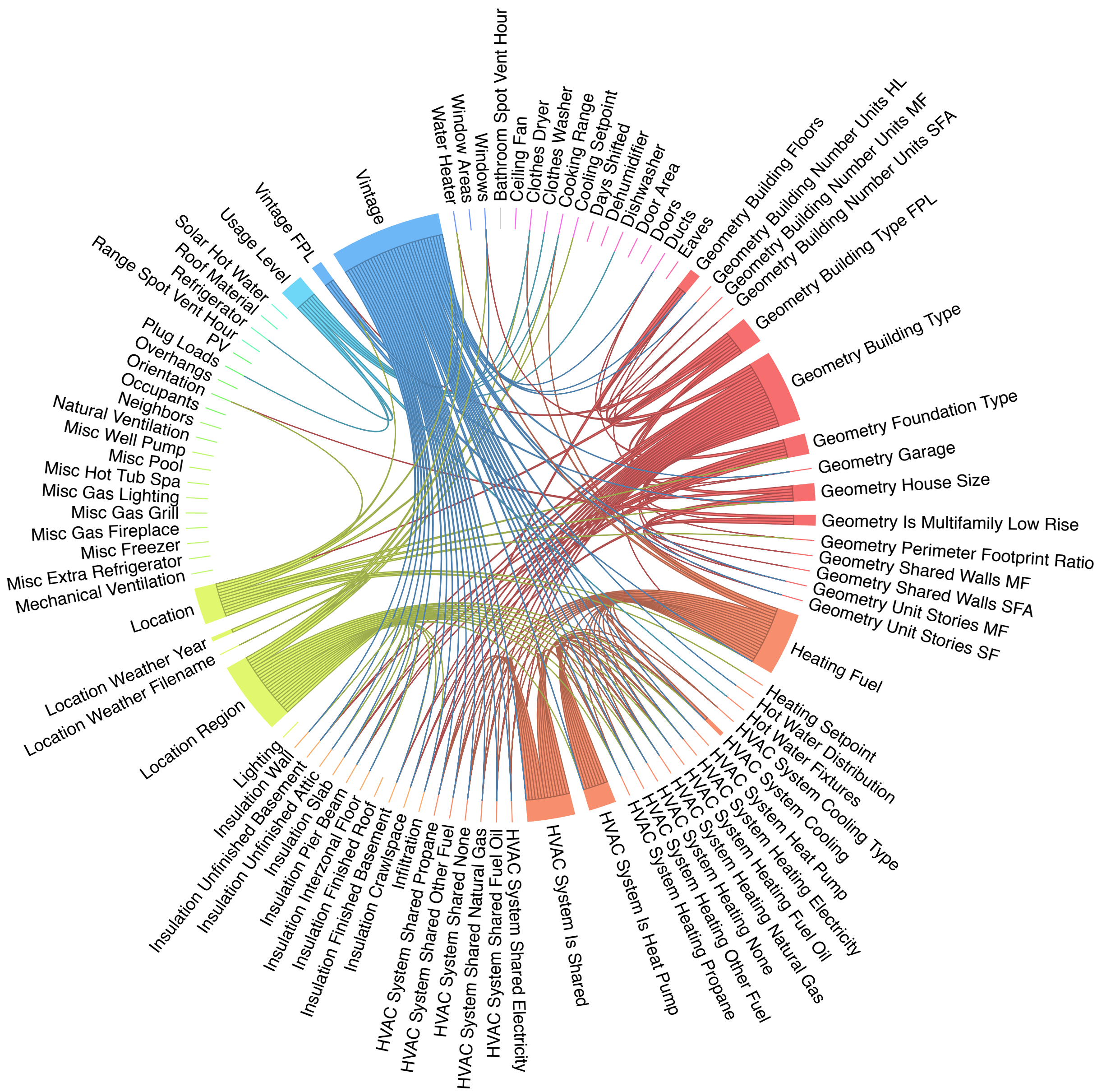


Figure 1. This chord diagram shows the dependency structure of residential building characteristics used to develop ResStock simulations. Vintage, location, building type, and heating fuel are among the most important parameters, upon which many of the other parameters' distributions depend. Note: PV = photovoltaics; HL = high rise/low rise; FPL = federal poverty level; SFA = single-family attached; HVAC = heating, ventilating, and air conditioning; MF = multifamily; SF = single family

26 Different definitions of cost-effectiveness can be used. Previous applications have focused on positive net present value or simple pay-back periods less than 5 years, both considering the costs and benefits from the building owners' perspective.

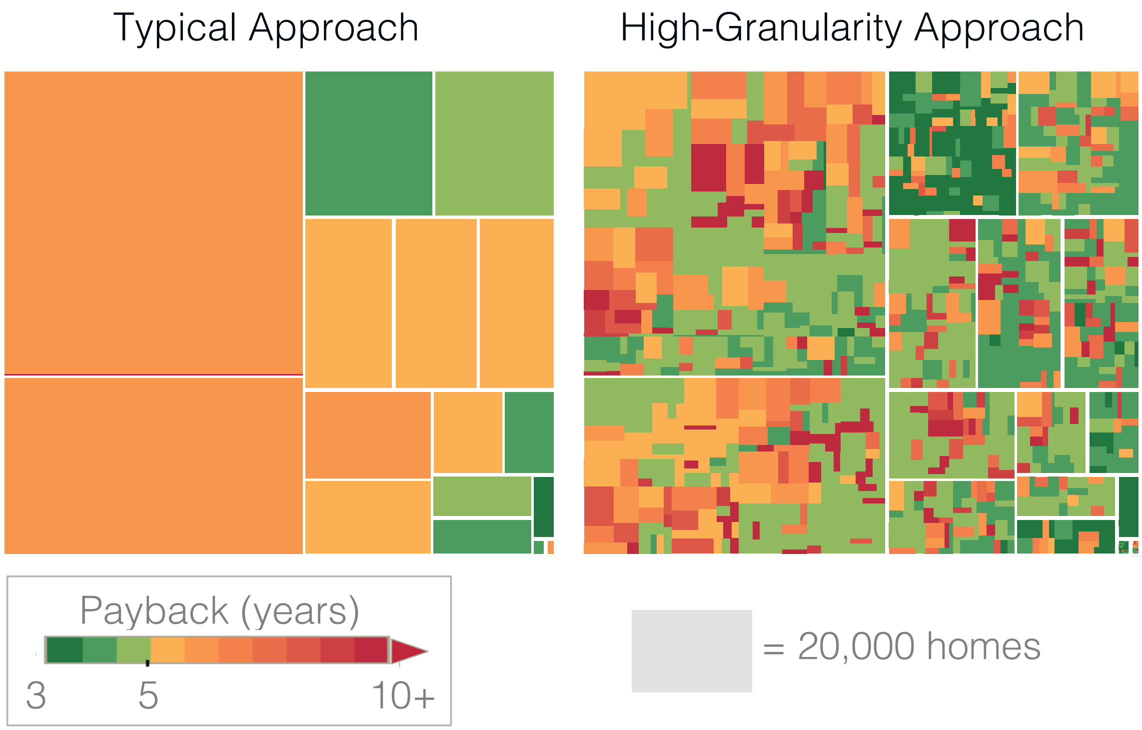


Figure 2. Example pay-back period analysis for wall cavity insulation upgrade in electrically heated homes in Washington and Oregon. Low-resolution stock modeling (left) can result in misleading, all-or-nothing results—the chosen prototype may resemble much less than 50% of the buildings it is intended to represent. High-resolution stock modeling (right) leads to more accurate estimates of savings potential, as well as the ability to target housing stock segments for particular efficiency measures.

sector (e.g., New York State[27]) as well as a more comprehensive energy-efficiency potential report for the entire U.S. residential sector.[28] For ResStock, there is also an interactive website for visualizing the national-level results.

Applications of ResStock/ComStock

The ResStock/ComStock capabilities have already been used in a number of different applications. We detail these here, as well as a few applications that have not yet been deployed. We also overview the beneficiaries of the different applications.

CITY PLANNERS AND AGENCIES. City planners and agencies can utilize building stock analysis to answer larger-scale questions about energy use and quality of life across the city. Some applications in this area include:

- **Low-income energy-efficiency potential.** Building stock modeling maintains resolution of what is happening where in the city, so it can be useful to study the impact of efficiency on low-income and minority communities both to ensure that interventions are not overly burdensome for vulnerable populations and to find cost-effective pathways to reduce their energy bills and improve their quality of life.
- **GHG reduction and air quality improvements.** When energy use is linked to GHG and criteria air pollutants, it can be a powerful tool for studying emission reduction pathways. In the case of criteria air pollutants, which cause harm to the people and environment directly exposed to these emissions, stock modeling can be especially helpful not only for determining how to reduce emissions but also for where emission reductions will lead to the greatest amount of decreased human exposure.
- **Technology adoption scenarios.** In developing GHG reduction plans, cities might set high-level goals for

27 https://resstock.nrel.gov/factsheets/NY

28 Wilson, E., C. Christensen, S. Horowitz, J. Robertson, and J. Maguire. 2017. *Energy Efficiency Potential in the U.S. Single-Family Housing Stock*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-68670. https://www.nrel.gov/docs/fy18osti/68670.pdf.

sectorwide reductions, but pinpointing the exact technology improvements to be set into policy can be difficult. Stock modeling can link technology changes to energy and emission reductions, and whole suites of technology packages can be compared, along with the cost-effectiveness of these approaches.

UTILITIES. Utilities can use building stock analysis for longer-term planning of grid distribution operations by modeling future changes in energy demands and the impact of technology intervention on energy needs. Specifically, building stock modeling can be useful for:

- **Energy-efficiency program design.** Building stock analysis can be used to study the technical potential of energy efficiency to reduce demand in different types of buildings and the cost-effectiveness of different incentive programs.
- **Grid load modeling.** When ResStock/ComStock are calibrated to temporally resolute energy data, the models can be used to produce resolute load shapes of building energy demand. These can be useful in a variety of applications, such as planning for future distribution and transmission build-out needs or even designing the distribution grid of a new development.
- **Demand response.** Temporally calibrated load shapes can also be used to design demand response programs by modeling system response to a call. Building stock modeling can also be useful for modeling the technical potential of demand response under differing weather and grid conditions.

CITY RESIDENTS. Both home and business owners can reap cost, energy, and health benefits from improving the energy efficiency of the buildings. These benefits can be achieved both through larger-stroke efficiency initiatives or through specific-premise targeting. Example applications include:

- **Building-type improvements.** Building stock analysis can help identify cost-effective energy savings pathways for different types of customers and buildings across the city by locating buildings with the largest energy savings potential.

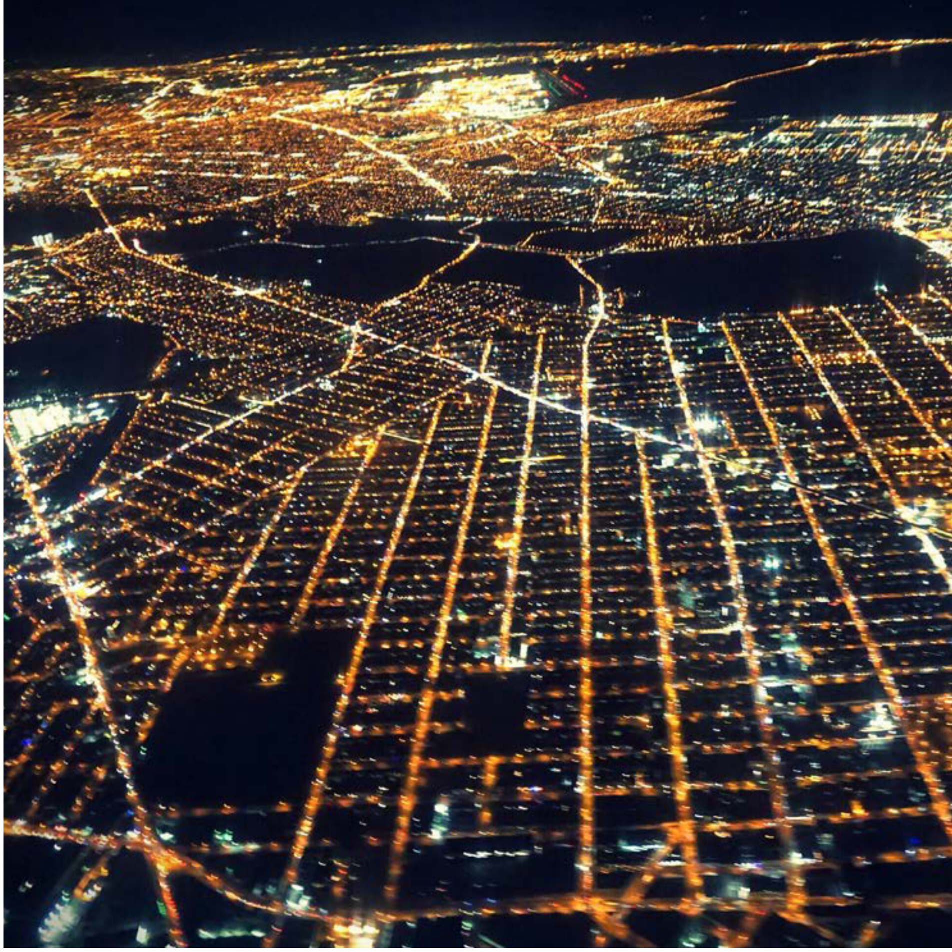


Photo from iStock, 507122054

- **Premise-level targeting.** Figure 3 shows how ResStock/ComStock analysis results can be matched to individual premises. This process automatically develops tailored energy-efficiency packages and savings predictions for individual premises, which can be used for targeting high-priority opportunities with tailored marketing materials or door-to-door interventions. By virtue of the ResStock/ComStock statistical modeling approach, the predicted savings are presented as a range that incorporates uncertainty about unknown building characteristics. For premises-level targeting, the range of predicted savings is narrowed by each subsequent step in the matching process by adding increasingly granular detail on building characteristics from sources such as a tax assessor database or utility bills. A guided owner self-assessment or professional on-site audit is an optional final step to gain maximum confidence in predicted savings and return on investment. The savings predictions can be presented as a building owner dashboard to communicate the value proposition of investing in building energy upgrades.

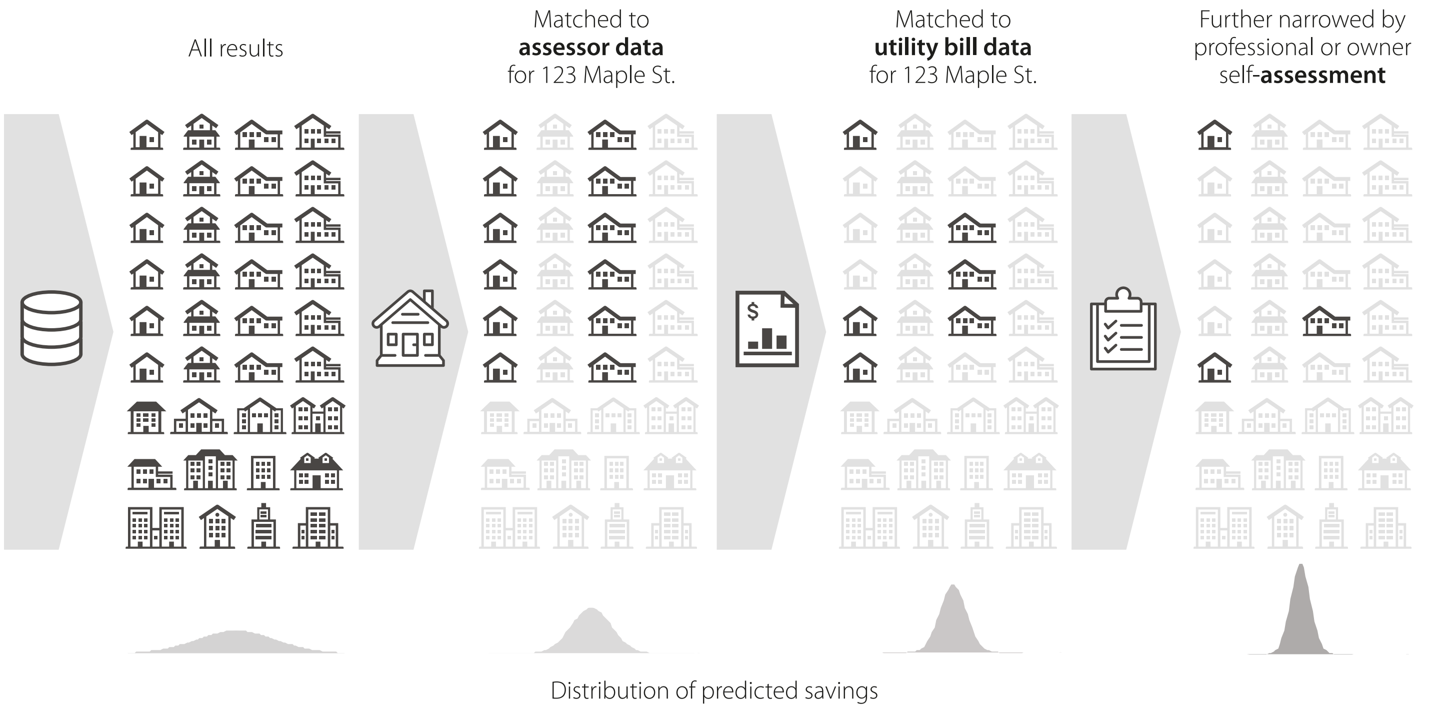


Figure 3. This diagram illustrates how analysis results can be matched to an individual premise (e.g., 123 Maple St.) using assessor data for that premise (floor area, vintage, heating fuel, and so on) and, if available, the customer's utility bill data.[29]

Beyond the national implementation, there have been several projects with cities and utilities using ResStock/ComStock in more localized scenarios to generate more detailed results. In this approach, instead of using the national "default" characteristics, local information on building characteristics and energy consumption are used to create a unique local model with more spatially detailed outputs than the national implementation. Example projects include:

- Radiant Labs has built a suite of analytics tools for the city of Boulder, Colorado, that leverages the ResStock analysis capabilities with city-specific inputs derived from local data sources. The analytics tools are helping Boulder develop city-specific strategies around energy efficiency and renewable heating and cooling. The targeting platform can be used to identify ideal candidates for deep home energy improvements, while a dashboard provides homeowners with the economic narrative for pursuing a deep energy reduction strategy.
- The city of Los Angeles and the Los Angeles Department of Water and Power have engaged NREL to help them achieve their 100% renewable energy goals. Los Angeles-specific versions of ResStock and ComStock are being developed to explore future building stock scenarios and how these scenarios affect the feasibility of their 100% renewable electricity supply target.[30]
- Working with the Bonneville Power Administration, NREL developed a version of ResStock specific to the Pacific Northwest region that it can use to optimize how energy-efficiency improvements are incentivized and how they tie into the electricity generation and distribution strategy for the region.

Status of ResStock and ComStock Capabilities

ResStock and ComStock are both tools undergoing continuous development by NREL. Here is an overview of the current capabilities of the models.

29 Monthly electricity and gas use data may be available from the utility company if they are a project partner, via an energy disclosure ordinance or via customer-enabled Green Button data. In some cases, subhourly electric meter data may be available to use for higher-resolution energy use matching.

30 https://www.ladwp.com/cs/idcplg?IdcService=GET_FILE&dDocName=OPLADWPCCB625209&RevisionSelectionMethod=LatestReleased

31 Radiant Labs: http://www.radiantlabs.co/

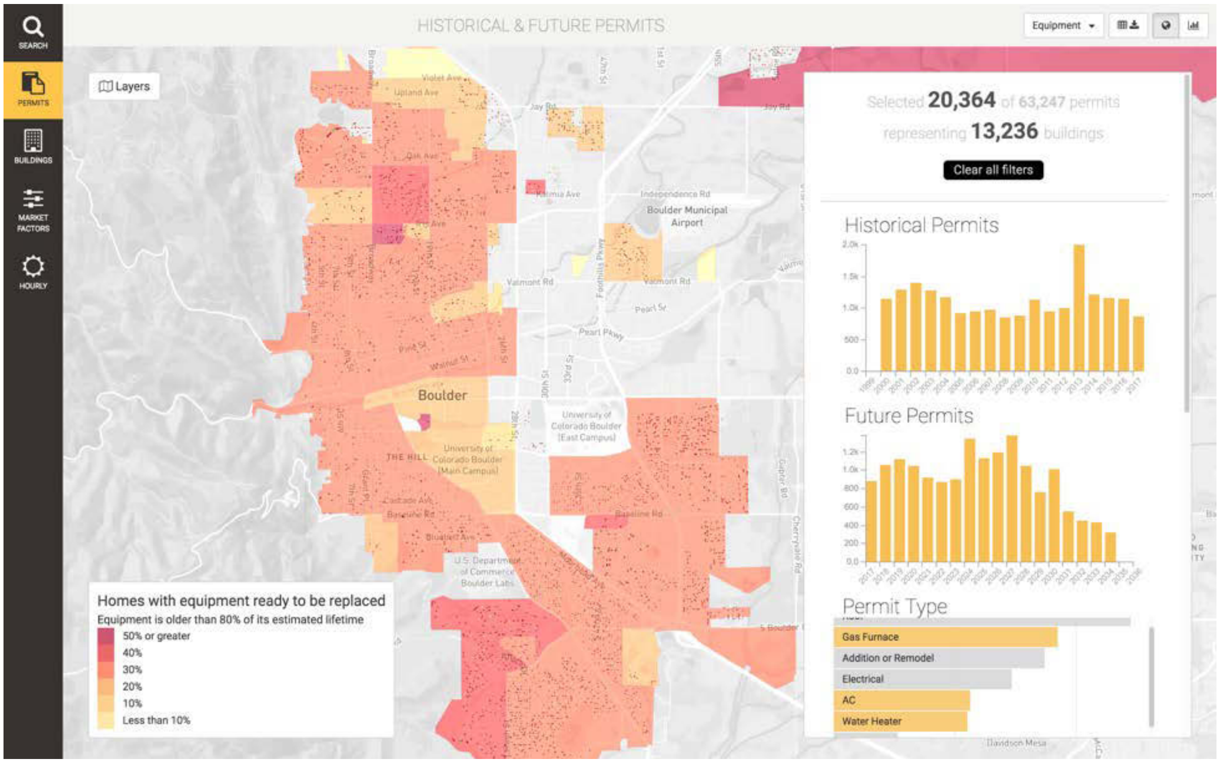


Figure 4. Example analytic output from Radiant Labs on equipment replacement potential by geography. Note: AC = air conditioning.[31]

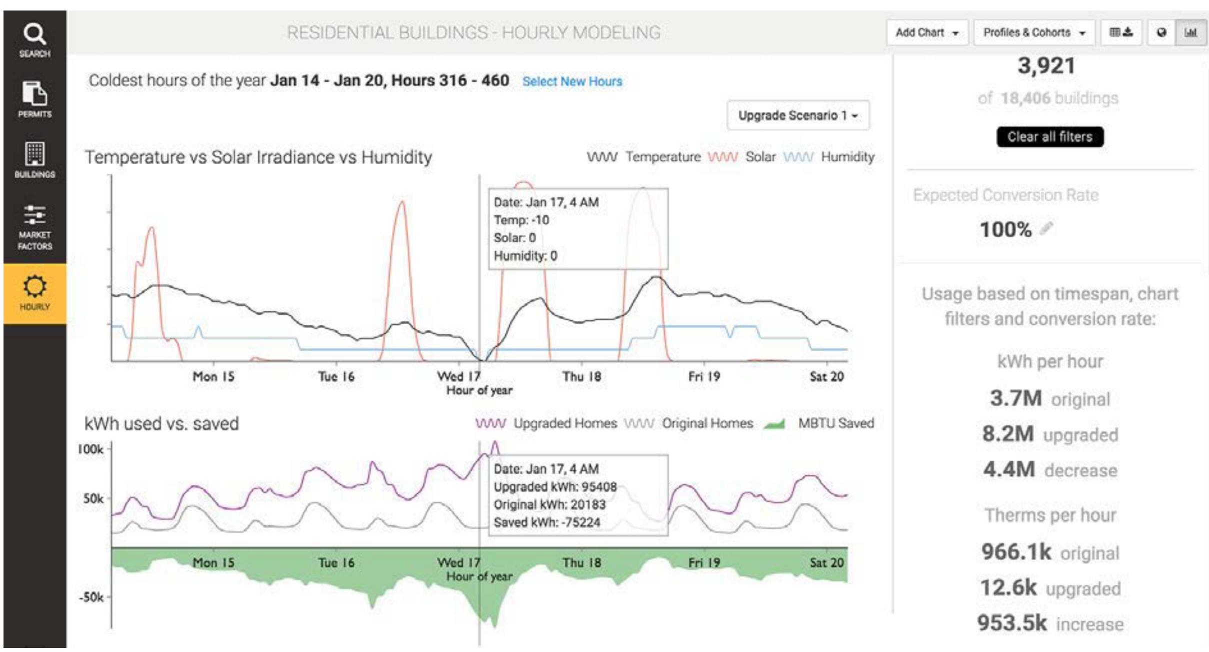


Figure 5. Example analytic output from Radiant Labs on equipment replacement potential by building type.[31]

RESSTOCK. Capabilities for the U.S. single-family detached housing stock are currently free and publicly available for use (see documentation at https://resstock.nrel.gov/). Capabilities and input characteristics data for multifamily buildings with three stories or fewer are now available. Users can contact resstock@nrel.gov to learn about options for obtaining training or technical support from NREL, or to be referred to experienced third-party ResStock consultants.

COMSTOCK. Capabilities for modeling the U.S. commercial building stock, including multifamily and mixed-use buildings with four or more stories, are currently under development. It is expected that the analysis capabilities will be ready for widespread use in 2020, though NREL analysts are using in-house versions for specific city-scale applications as of 2019. Contact comstock@nrel.gov for additional information on ComStock.

MEASURES. ResStock users can specify an array of residential energy-efficiency measures, along with installation costs (e.g., cost per square foot of attic area plus fixed cost) and logic for applying measures (e.g., insulate attic to R-49 if existing insulation is less than R-19).[32] Although the current array of measures covers most of the important residential opportunities nationwide, there are some measures that lack underlying OpenStudio®/EnergyPlus models and may require additional development effort by NREL or others with OpenStudio/EnergyPlus development experience.[33] Examples include thermostatic radiator valves, advanced boiler controls, and evaporative coolers. ComStock users can make use of the array of commercial building measures available in the crowdsourced Building Component Library.[34]

OUTPUTS. Standard outputs of ResStock and ComStock analysis are energy consumption by fuel and end use, as well as savings for upgrade measures and packages included in the analysis. Standard economic outputs include upgrade costs, energy cost savings, net present value, and simple pay-back period. Upgrade costs can be used as a proxy for potential revenue to the local businesses performing the upgrades. Postprocessing scripts can be modified to calculate additional economic metrics, such as utility cost-effectiveness tests (e.g., total resource cost) or savings-to-investment ratio. Standard environmental metrics include greenhouse gas emissions and primary energy use, and postprocessing scripts can be modified to calculate additional metrics for avoided criteria air pollutants (e.g., fine particulate matter, sulfur oxide, and nitrogen oxides).

All of the previous outputs can be filtered or aggregated by building characteristics (location, building type, vintage, household income, and so on) or economic criteria (e.g., net present value greater than zero), to calculate technical or economic potential savings for a particular subset of buildings. Standard geographic resolution for national-scale analysis is at a county level, but use of tax assessor and other local data sources can provide confidence in census block or even premise-level results (with appropriate uncertainty ranges).

The outputs described here are saved to a single table in a comma-separated value format, with rows for each simulation including baseline and upgrade simulations, and columns for each building characteristic parameter (vintage, heating fuel, and so on) or output metric (e.g., annual utility bill savings). Hourly or subhourly time series for each simulation's end-use category can also be produced, each of which maps to a simulation row in the main results file.

Potential Timeline and Costs for City-Scale Building Stock Analysis

In this section, we estimate the timeline and budget for running a building stock energy-efficiency analysis using NREL's ResStock and ComStock tools for a city, such as NYC, that has prepared using the steps listed previously. There are two main components to the modeling cost: (1) the cost of labor from NREL employees or trained consultants and (2) the computational resources necessary to actually run the models.

Labor Costs

The budget for a city-scale analysis will vary widely depending on the scope of analysis involved and how much local data is being used. Contact resstock@nrel.gov to learn about options for contracting with NREL, or to be referred to experienced third-party ResStock consultants.

32 See Tables 9 and 10 in the following report for examples: https://www.nrel.gov/docs/fy18osti/68670.pdf.

33 Residential modeling capabilities are tracked in the public repository at https://github.com/NREL/OpenStudio-BuildStock/tree/master/resources/measures.

34 https://bcl.nrel.gov/

At a high level, tasks to be performed as part of an analysis typically include:

1. **Data collection, processing, and GIS:** geocoding, spatial joins, footprint analysis/processing, data cleaning, permit analysis, formatting for ResStock/ComStock input
2. **Energy modeling:** scenario definition, preliminary technology assessment, modeling of stock scenarios, optional hourly load analysis, joining rooftop solar potential, validation if consumption data exists
3. **Financial modeling:** cash flow analysis based on local market conditions
4. **Visualization of results.**

Computational Costs

ResStock and ComStock are typically run using either cloud computing through Amazon Web Services[35] or NREL high-performance computers.[36] As an example of the general costs for computation, in a similar project it cost $2,500 to simulate five retrofit scenarios for models representing 100,000 residential buildings. Commercial building stock analysis will be more expensive, as simulation runtimes are longer for larger buildings. Efforts are underway to make use of Amazon EC2 Spot Instance Pricing, which could reduce computational costs by 50–80%.

Timeline

Based on previous work with other cities, we estimate that an initial building stock analysis model for a midsize to large city using ResStock and ComStock could be developed in about 6 months. Additional refinement of the results and iterative feedback with city stakeholders could take an additional 6 months, for a total timeline of about 12 months. Once established, the model could be updated with new scenarios and completely rerun in approximately 2–4 weeks. This approach could be used for annual results updates to keep the model current.

Cover photo from iStock 908031820

35 https://aws.amazon.com/

36 https://www.nrel.gov/esif/labs-hpc.html

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

NREL/TP-5500-71727 • July 2019