An Integrated Approach to Water & Energy Infrastructure Decision Making Using the MARKAL Framework: A Case Study of New York City

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ABSTRACT

Meeting increased demand for energy and water combined with increased resource scarcity exacerbated by climate change presents a significant challenge to many cities around the world. New York City (NYC), whose infrastructure is among the oldest in the U.S., will require replacement, expansion and upgrades over the coming decades to serve a steadily growing population. An integrated approach to water and energy planning can identify and evaluate policy scenarios that leverage opportunities for resource efficiency, cost reductions, and long-term sustainability. This integrated strategy could help urban and regional planners explore possibilities to foster more resilient urban ecosystems.

This paper describes the development of a community-scale decision support tool designed to examine water and energy consumption and management scenarios under different policy scenarios in NYC. The MARKet ALlocation (MARKAL) energy-environmental-economic modeling framework is utilized to generate site specific database for NYC that focuses on the building sector, energy, water supply and wastewater treatment infrastructure to capture and analyze the water-energy nexus. The NYC community MARKAL database includes reference building energy profiles and future energy efficiency retrofits, water and wastewater infrastructure, green infrastructure alternatives (e.g., green roofs), distributed energy options (e.g. roof-top solar PV and combined heat and power plants). The framework will enable users to forecast building energy consumption, potable water use and storm water runoff and treatment options by facilitating case studies in other cities. This paper provides an overview of the NYC community MARKAL development process, data sources, preliminary calibration results against actual energy and water consumption data, and a narrative for intended scenario analysis.

BACKGROUND

The Energy and Climate Assessment Team within the Office of Research and Development at the U.S. EPA has developed a database representing the entire U.S. energy system encompassing nine census divisions (known as the EPAUS9r database) to use within the MARKet ALlocation (MARKAL) modeling framework (USEPA, 2013). MARKAL is an engineering-economic mixed-integer linear programming model that solves for the least-cost system-wide solution for meeting end-use energy service demands, given primary energy resources for a given region (Fishbone et al., 1981). The basis of the MARKAL modeling framework is a network diagram called the Reference Energy System (RES), which depicts an energy system from resource to end-use demand. Data for the EPAUS9r model are derived primarily from the U.S. Energy Information Administration (EIA)'s NEMS model, and results are calibrated to the Annual Energy Outlook 2014 (USEIA, 2014).

The goal of this project is to develop a database for addressing issues faced by communities related to the energy and water nexus. The MARKAL framework can also allow tracking of water and wastewater commodities similar to energy. Segerstrom (2011) explored this and developed further expansion of RES to include water. We selected NYC for various reasons including being an early adopter of greenhouse gas (GHG) reduction goals through energy efficiency and renewable energy (EE&RE) in the building sector and awareness of vulnerabilities due to sea level rise and the possible risks posed to the energy and water infrastructure. The U.S. EPA's New York City Community MARKAL (EPANYC5r) database uses existing and future technology data (e.g., capital and O&M costs, fuel use efficiency, availability, etc.) data from the EPAUS9r framework, and also relies on the site specific fuel, energy, and water data published by the New York City Department of Environmental Protection (NYC DEP), the New York State Energy Research & Development Authority (NYSERDA), and a variety of other local sources.

Researchers in academia, non-governmental organizations, and national laboratories use the MARKAL framework to model various applications from evaluating energy technology potentials to finding long-term emission reduction strategies within energy system (Segerstrom (2011), Bhatt et al (2008), Cameron et al. (2014), and Aitken et al. (2015)). The MARKAL framework includes end-use demands for energy services (e.g., building space heating and cooling, water heating, and process heat for industrial facilities, vehicle miles traveled in light and heavy duty transportation sector) and supply curves for primary energy carriers including coal, natural gas, crude oil, biomass feedstocks, and other non-biomass renewable resources. Energy technologies (e.g., electric power plants, refineries, combined heat and power) are deployed based on their initial capital cost, variable and fixed operation and maintenance (O&M) costs, and performance (capacity, efficiency, and availability) parameters. MARKAL determines the optimal mix of energy technologies and fuels, solving for the lowest system-wide cost, while still meeting additional constraints such as criteria pollutant and GHG emissions limits, technology deployment goals, and renewable energy standards over the 2010-2055 time period. The applications include what-if scenarios to evaluate the evolution of energy system under different policies, or evaluation of specific future technology under various resource and technology penetration assumptions.

COMMUNITY MARKAL FRAMEWORK – EPANYC5r

The EPANYC5r database models five boroughs of NYC in five regions (R1 through R5). Primary energy resources (e.g. coal, oil and natural gas) are extracted and delivered to a supply region (henceforth referred to as R0) that represents the Northeast and Mid-Atlantic census divisions. Energy commodities are pulled through technologies (e.g. electric power plants, oil refineries, fuel distribution pipelines) to meet end-use service demands in the residential and commercial building sector such as space heating, space cooling, etc. A variety of demand technologies are represented in the database, e.g., electric furnaces vs. natural gas furnaces for space heating. Five boroughs of NYC as separate regions (R1 through R5) are linked to the supply region, and each other, through trade linkages that allow energy commodities to flow across regional boundaries. For example, NYC does not have sufficient electric generating capacity to meet load during extreme peak demand events, but the city can access wholesale electricity markets through transmission lines connecting each borough to Long Island, New Jersey, and Westchester County. Liquid fuels, natural gas and water commodities are allowed to flow between boroughs that border one another, as well as the supply region. The trade links associated with electricity, water, wastewater, oil and gas are shown in Figure 1. All links are applicable to all commodities except for R3, Staten Island, trades water with R1 and R2.

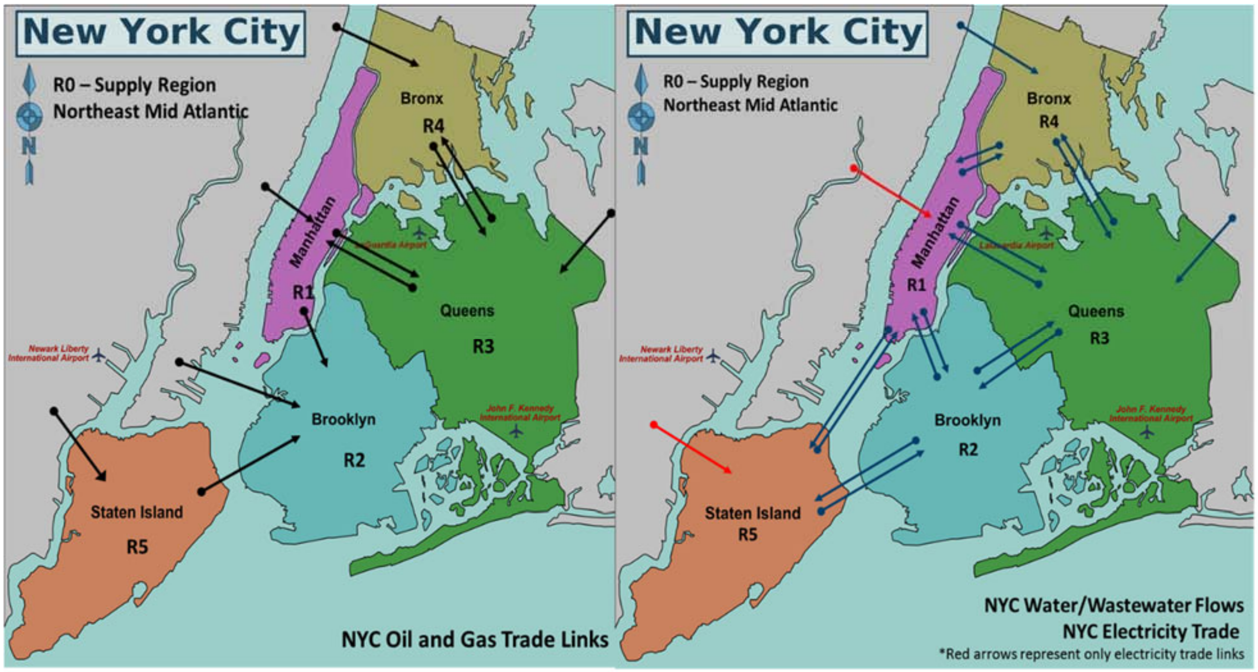

Figure 1. Trade links between NYC boroughs for electricity, water, oil and natural gas commodities in the EPANYC5r database

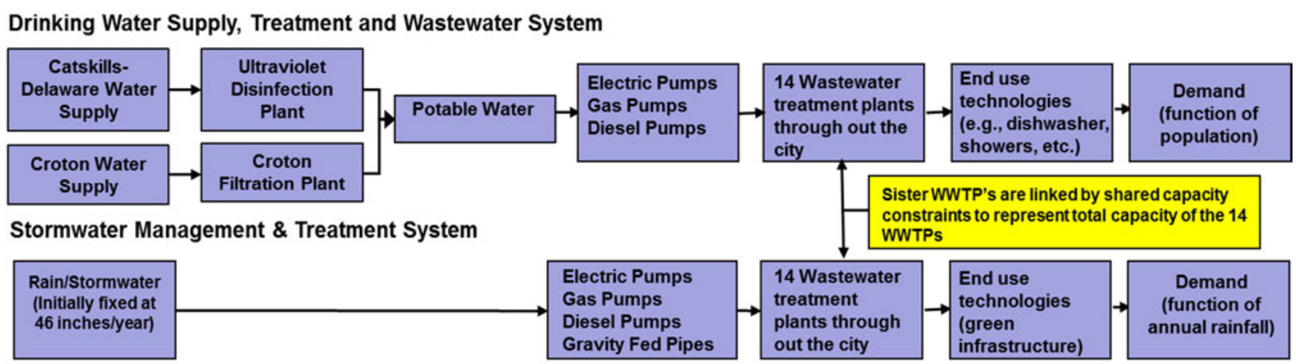

Figure 2. Reference Water System represented for the drinking water and stormwater commodity pathways in the EPANYC5r database

One of the key contributions of this research is to model the water and wastewater system along with the energy system to capture the energy-water nexus. We apply the RES concept to the water system to capture water supply, distribution, use in buildings and collection and treatment of wastewater along with stormwater. Similar to the energy system, starting from the water supply, each component of the water system is added to the database. Water and wastewater flow through the water and wastewater treatment system to meet end use demand. The end use demand is quantified by population or number of occupants in the modeled building type. Using population as demand allows the amount of drinking water to meet population needs and be determined endogenously in the modeling framework. Water demand per person per appliance or service such as showers or faucets is represented exogenously. Depending on the efficiency and cost of water technologies, the model determines the mix of them to meet the demand of each region. Using this modeling approach allows the user to have the flexibility of comparing different approaches to reducing water demand or stormwater runoff through efficiency improvements. Figure 2 illustrates the Reference Water System for modeling the drinking water and stormwater commodity pathways from initial supply to end-use in the MARKAL framework. The drinking water and stormwater systems were treated as two separate pathways because they have separate end-use demands (i.e., population for drinking water and million metric tonnes of rainfall for stormwater). NYC has a combined sewer and stormwater system, therefore the wastewater treatment plants (WWTP) in the city (14 of them) treat both flows. In the modeling structure, the separate systems are linked to each other through a capacity constraint so that the total capacity should not exceed the existing installed capacity.

The EPANYC5r database and corresponding reference case is calibrated to 2010 data reported in the NYC Greenhouse Gas Inventory (NYC GHGI) in terms of energy consumption and emissions (City of New York, 2014). Data from several NYC DEP sources were used to calibrate water consumption in the residential and commercial sectors across the city's five boroughs.

DATA SOURCES for ENERGY SYSTEM

The EPANYC5r database draws upon a variety of data sources to calibrate to actual energy and water consumption in the building sector. Energy consumption in NYC is dominated by residential and commercial buildings, which accounted for 87% of non-transportation energy consumption (2012 NYC GHGI). The EPANYC5r database was calibrated against 2010 energy consumption data reported in the 2012 NYC GHGI. The 2012 NYC GHGI reports an aggregate figure for year 2010 building energy consumption. The 2013 NYC GHGI has detailed breakdown for energy consumption for individual sectors such as residential, commercial and industrial buildings. We applied the percentage breakdown of energy consumption by residential, commercial and industrial buildings from the 2013 NYC GHGI to 2010 data in the 2012 NYC GHGI. For example, residential energy consumption accounted for 48% of total building energy consumption in 2013 NYC GHGI. Applying that percentage to total building energy consumption of 610 Petajoules (PJ) results in estimated residential consumption of 92 PJ in 2010.

The EPANYC5r database is based on building-level data retrieved from the NYC Planning Department's PLUTO dataset (NYC PD, 2015). The PLUTO dataset contains detailed information for every tax parcel in NYC, including total indoor area (ft^2) and building type identifiers that were used to develop building archetypes and estimated annual energy and water demand. The data processing focused on aggregating the 280 PLUTO building types into 19 categories used to populate the EPANYC5r database. For example, PLUTO contains 14 unique building types that describe 1-2 family dwellings which were aggregated into a single category called "1-2 family dwellings" in the EPANYC5r database. After the raw PLUTO data was aggregated up to 19 building categories, they were then allocated to three building sectors (residential, commercial, industrial) to align with the energy and emissions data reported in the NYC GHGI. Table 1 displays the building categories represent preliminary in the EPANYC5r database along with currently assumed values of energy use intensity (EUI) factors.

The floor space (ft^2) of each building category serves as the starting point for estimating annual energy consumption (electricity, natural gas, distillate #2 heating oil, and low sulfur residual fuel oil) and end-use energy demands. Energy consumption and end-use energy demand are estimated using EUI factors for each fuel type. NYC Local Law 84 requires all buildings larger than 50,000 ft^2 to report energy and water consumption for benchmarking purposes. This data was useful in determining the mix of low/high efficiency buildings, but EUI was reported in total kBtu/ft^2 rather than fuel specific EUI coefficients. The EPANYC5r database relies on EUI coefficients and end use demand percentages derived from data from the Commercial Building Energy Consumption Survey (CBECS) data for the Northeast region (U.S. EIA, 2015). End use energy demands are estimated by multiplying total energy consumption by a percentage associated with each end use. The EUI factors used in the EPANYC5r model were adjusted to calibrate the model results to data reported in the NYC GHGI. Table 1 summarizes the EUI factors used to estimate electricity, natural gas, and distillate heating oil consumption in residential, commercial, and industrial buildings. **Error! Reference source not found.**a summarizes the spatial distribution of energy consumption reported by Howard et al. (2012).

Table 1. Energy Use Intensity (EUI) Factors Used in the EPANYC5r Database

Sector	Building Type	Electricity (kWh/ft^2)	Natural Gas (kBtu/ft^2)	#2 Heating Oil (kBtu/ft^2)
Residential	1-2 Family Homes	2.5	45	30
Residential	Apt/Condo/Hotel	2.5	45	30
Commercial	Airport	20	60	40
Commercial	Auto Services	20	60	40
Commercial	Church/Mission	10	60	40
Commercial	College/University	10	60	40
Commercial	Education K12	10	60	40
Commercial	Government	20	60	40
Commercial	Hospital/Clinic	20	60	40
Commercial	Other	10	50	40
Commercial	Outdoor	0	0	0
Commercial	Parking Structures	3.5	0	0
Commercial	Office/Retail	10	55	40
Commercial	Theater	10	50	40
Commercial	Warehouse	10	50	40
Industrial	Industrial	100	250	100
Industrial	Port or Shipping	100	250	100
Industrial	Electric/Gas Utility	100	250	100
Industrial	Utility Other	100	250	100

DATA SOURCES for WATER SYSTEM

The EPANYC5r database incorporates and models water supply, treatment, distribution, wastewater collection and treatment, and end-use water demand for the buildings sector for each of the boroughs. This component was added to the EPANYC5r database using a variety of reports and data from the NYC DEP. Daily and annual water consumption data were drawn from the NYC DEP's 2014 Water Demand Management Plan (NYC DEP, 2014). According to this data, NYC's daily water consumption is approximately 835 million gallons per day (MGD). The total amount of water supplied was estimated to be 1,071 MGD with approximately 21% of total supply attributed to unaccounted water (UAW) losses. NYC DEP data was also used to calibrate water consumption in each of the five boroughs. Data for fiscal year 2010-2011 show that Manhattan was the most water intensive borough with annual metered supply of 333.97 MGD, followed by Brooklyn with 295.89 MGD, the Bronx with 203.01 MGD, Queens with 196.96 MGD, and Staten Island with 46.03 MGD (NYC DEP, 2012). A breakdown of city-wide water consumption in the residential and commercial building sectors was available, but borough-level consumption data for those sectors was not publicly available. **Error! Reference source not found.** summarizes reported water consumption data published by NYC DEP.

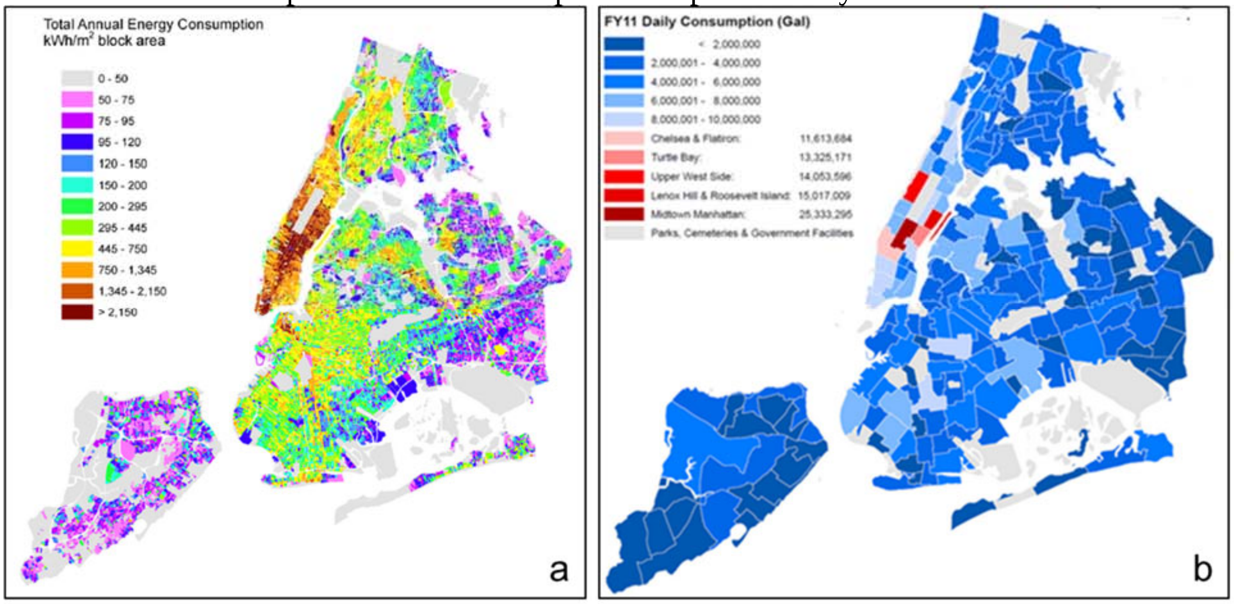

Figure 3. New York City energy consumption by block area (3a) and water consumption by neighborhood (3b) Source: Howard et al, 2012 and NYCDEP, 2012a.

End use water demand in the EPANYC5r database was estimated with use patterns for common water fixtures and appliances (e.g. average shower length, flushes per day, dishwasher loads per week) and flow/consumption rates for low-flow and high-flow fixtures (e.g. gallons per flush, gallons per minute for showers and faucets, gallons per load for dishwashers and clothes washing machines). The EPANYC5r database applies the use patterns for typical water fixtures and appliances into the three building sectors described earlier (residential, commercial and industrial). Water consumption estimates are based on assumptions used by the Pacific Institute in the organizations *Commercial Water Use and Potential Savings* report (Gleick et al. 2003). The report contains water fixture and appliance use estimates for office buildings, hotels, hospitals, laundromats, restaurants, grocery stores, retail stores, and schools. Estimates for water consumption in residential buildings are generated using typical consumption habits reported by the NYC DEP for typical 1-2 family homes (NYC DEP 2012b). NYC DEP data show that toilets represent the largest share of residential water demand at 28%, followed by laundry at 24%, showers at 18%, faucets at 16%, leaks at 10%, and dishwashing at 2% (NYC DEP 2014).

The EPANYC5r database includes energy consumption and emissions associated with water, wastewater and storm water infrastructure system (including supply, distribution and treatment). Each of NYC's fourteen wastewater treatment plants (WWTP) are represented in the community MARKAL framework, as well as the two major water filtration plants serving the NYC metro area. Electricity and natural gas consumption by WWTPs is estimated using energy intensity coefficients measured in PJ/million metric tonnes (MMT) of water throughput after converting values retrieved from NYSERDA energy audits that contain electricity consumption (kWh/MGD) and natural gas consumption (mmBtu/MGD) in facilities serving the Town of Tonawanda, the City of Ithaca, and a survey of WWTPs in other northeastern states (NYSERDA, 2005). The efficiency of WWTPs improves with the scale of the facility, ranging from 1,070 kWh/MG for activated sludge WWTPs with a daily flow capacity greater than 75

MGD to 4,100 kWh/MG for activated sludge WWTPs with daily flow capacity lower than 1 MGD (NYSERDA 2008). All of the WWTPs serving NYC have rated flow capacities of at least 40 MGD, therefore an EUI of 1,630 kWh/MG was used for the four WWTPs smaller than 75MGD, and an EUI of 1,070 kWh/MG was used for the ten WWTPs larger than 100 MGD resulting in a citywide average of 1,227 kWh/MG. An EUI of 1.2 mmBtu/MG was applied to all fourteen NYC WWTPs to estimate natural gas consumption based on a review of NYSERDA energy audits.

Table 2 summarizes the use patterns and water consumption for fixtures and appliances included in the EPANYC5r database.

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Table 2. Water Use Patterns & Consumption Variables Used in EPANYC5r Database

	Residential	Commercial	Industrial
Clothes Washing Machines			
Energy Star Unit (gallons/load) *	15	15	15
Low Efficiency Unit (gal/load) *	35	35	35
Loads per Week **	6	0	0
Showers			
Low Flow Shower (gallons/minute) *	1	1	1
High Flow Shower (gallons/minute) *	2.5	2.5	2.5
Avg. Shower Length (minutes) **	10	0	0
Faucets			
Avg. Minutes per Use **	1.0	0.5	0.5
Uses per Day **	5	3	3
Standard Flow Rate (gal/minute) *	2.2	2.2	2.2
Efficient Flow Rate (gal/minute) *	1.0	1.0	1.0
Dishwashers			
Buildings with Dishwashers (%) **	50%	25%	25%

Loads per Week **	5	0	0
Standard Consumption (gal/load) *	10	10	10
Efficient Consumption (gal/load) *	4	4	4
Toilets			
Flushes/Person/Day **	4.0	2.0	2.0
Standard (gal/flush) *	5.0	5.0	5.0
Efficient (gal/flush) *	1.6	1.6	1.6

** Water consumption rates for appliances and fixtures were drawn from the U.S. EPA's Water Sense website, the U.S. DOE's Energy Star website, and the Pacific Institute's Waste Not, Want Not Report.*
*** Values are initial assumptions used to calibrate the EPANYC5r model against reported consumption data.*

NYC DEP (2014) and NYSERDA (2008) energy audits used to estimate annual energy consumption by water disinfection and treatment facilities and pumping stations. The NYC's water distribution consumes approximately 60-70 kWh/MG a relatively low energy consumption by comparison to some other parts of United States. For example, water supply and distribution in southern California requires approximately 8,900 kWh/MG because water must be pumped over long distances and mountainous terrain to reach Los Angeles, San Diego and other large urban areas (CEC 2005). NYC GHGI data for total electricity, natural gas and fuel oil consumption by all wastewater treatment facilities was used to calibrate the EPANYC5r database. Figure 4 summarize the location, capacity and energy consumption of the fourteen WWTPs and 96 pumping stations included in the EPANYC5r database.

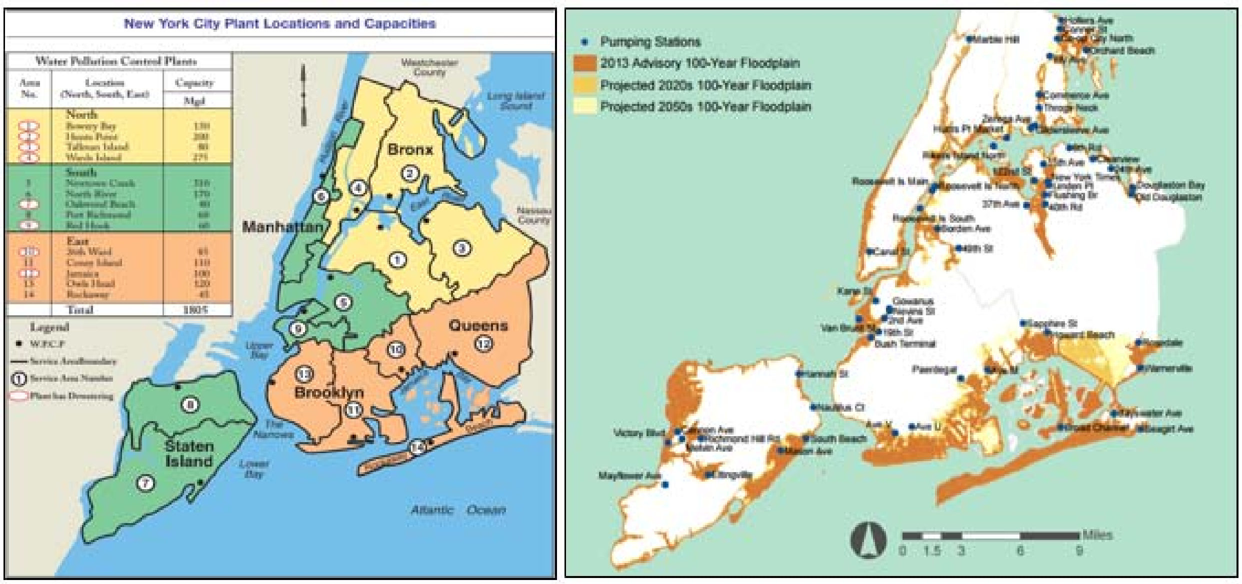

Figure 4. Location and capacity of NYC wastewater treatment plants (left) and water pumping stations (right) in New York City. Source: NYCDEP 2014.

PRELIMINARY CALIBRATION RESULTS

The EPANYC5r database reference case is being calibrated to 2010 energy consumption and emissions data reported in the 2011 NYC GHGI, and water consumption data reported by the NYC DEP for fiscal year 2010-2011(July 1st, 2010 – June 30th, 2011). These data sources allowed us to compare the reference case for future energy trends at the city-level for the residential, commercial, industrial, water and wastewater infrastructure sectors. For water consumption, the model's performance was compared against borough-level totals for metered supply and consumption, as well as city-level totals for the residential and commercial sectors. The Figure 5 displays the initial calibration results for the residential, commercial and industrial building fuel and electricity consumption. Total city-wide estimated energy use in NYC was 474.2 PJ/year compared against 569.9 PJ/year (excluding #4 and #6 Fuel Oil consumption). The year 2010 consumption reported in the NYC GHGI is 627.5 PJ/yr which includes #2, #4 and #6 Fuel oil. Our calibration is still in progress to achieve close to the reported numbers.

Total water consumption calibration results (Figure 6) for 2010 are much more closely aligned with data reported by the NYC DEP. End use consumption estimates for the five boroughs were all within +/- 4MGD of actual data collected during NYC DEP's 2010-2011 fiscal year (NYC DEP, 2012). Total city-wide water consumption in the reference case was 813 MGD compared against reported data showing 814 MGD. Total supply, after accounting for UAW losses, was 1,077 MGD compared with reported data showing 1,078 MGD. Figure 6 also presents breakdown of residential water use by various end use types, our calibration is still progress to align our results with the reported values.

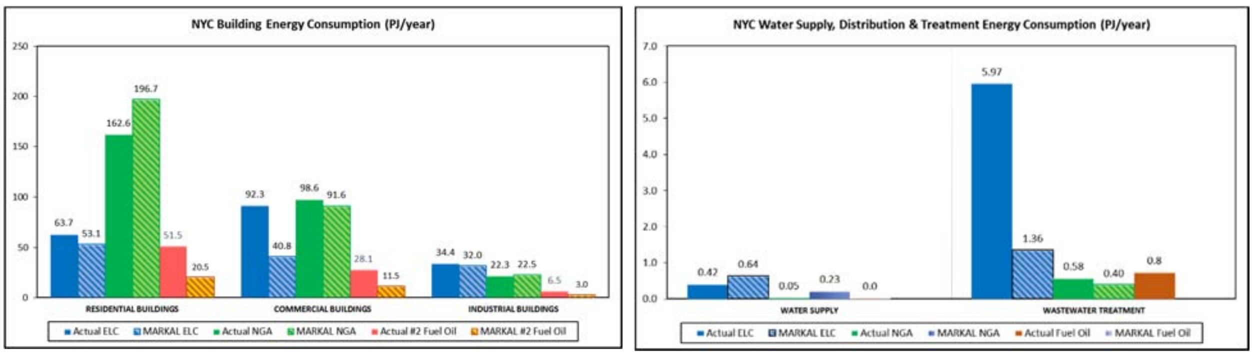

Figure 5. Estimated energy consumption in NYC (left) and energy use for water supply & treatment (right)

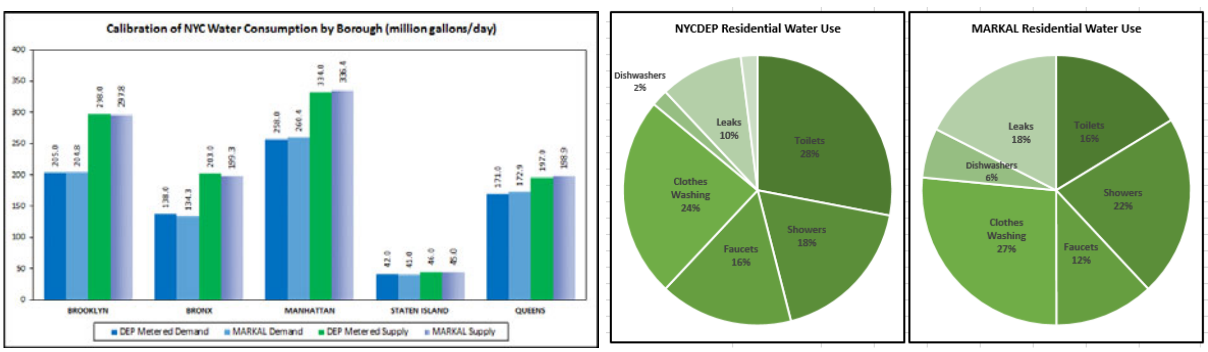

Figure 6. Estimated water use in NYC boroughs (left), and residential buildings by end use (right)

The EPANYC5r database tracks emissions of SO2, NOx, CO2, PM10, CH4, and VOCs. **Error! Reference source not found.** displays the borough level emissions resulted from preliminary calibration of the EPANYC5r. The NYC GHGI reports carbon dioxide equivalents (CO2e).

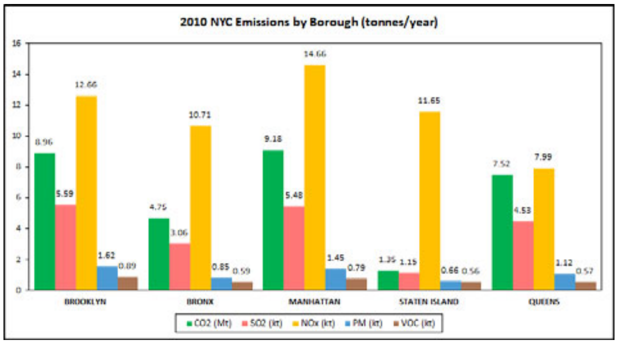

Figure 7. Estimated emissions in NYC boroughs

Table 3 presents detailed GHG emissions breakdown for reported and EPANYC5r database results. Citywide CO2e emissions estimates from the EPANYC5r model were 45.2 million metric tonnes compared with reported emissions of 40.7 million metric tonnes. Additional calibration work is in progress to address the difference in sector-specific GHG emissions. The discrepancies in the calibration results are mainly due to the lack of information on technology stock in the buildings and their corresponding fuel and electricity consumption as well as efficiencies. To mimic the conditions in the variety of aggregated building types, we started with some base assumptions on the suite of technologies and their fuel and electricity consumption as well as efficiency. From there, the calibration will continue until we reach small deviation from actual reported values.

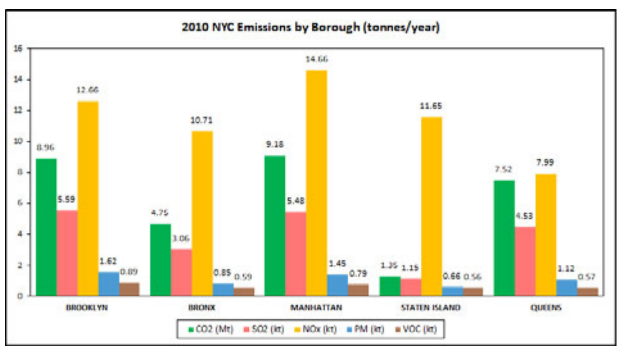

Figure 7. Estimated emissions in NYC boroughs

Table 3. Reported versus modeled CO2e emissions

Sector	NYCDEP CO_2e	MARKAL CO_2	MARKAL CH_4	MARKAL CO_2e
Residential	19.7	19.7		19.7
Commercial	16.1	9.8		9.8
Industrial	4.6	2.2		2.2
NG Distribution	0.3	*	-	-
NG Supply	Not Reported	*	0.5	13.4
Wastewater Treatment	0.3	*		
Water Supply	>0.1	*		
NYC Totals	**40.7**	**31.8**	**0.5**	**45.2**

** Still in progress to be incorporated into the database*

DISCUSSION and FUTURE DIRECTIONS

The preliminary calibration results demonstrate the viability of the community scale MARKAL energy modeling framework for performing scenario analysis at a city and regional level. The next step in our research is to calibrate the EPANYC5r MARKAL database within small deviations of the reported values, then have it peer-reviewed, and make it available to public. Stakeholder driven case studies will then be developed to aid decision makers in energy and water infrastructure planning.

Specifically, case studies for NYC will analyze a variety of scenarios for long-term energy and water consumption planning activities. Future applications for the community MARKAL model might include but are not limited to evaluation of (1) building energy efficiency benchmarking programs, (2) city and regional emissions reduction strategies targeting buildings and transportation sector, (3) city and regional level renewable energy standards, (4) forecasting energy consumption related to water supply and treatment, and (5) stormwater reduction through deployment of green infrastructure (e.g., green roofs).

The EPANYC5r database will serve as an example for other cities and communities who are interested in leveraging the benefits of performing integrated water and energy planning as population growth and climate change place increasing pressure on aging infrastructure. The community MARKAL framework can be adapted for use in other cities or communities where underlying PLUTO data is available.

Local and regional authorities are facing challenges caused by climate change, urbanization, limited natural resources, environmental goals that conflict with economic development, and aging infrastructure that will require significant upgrades or replacement in coming decades. The community MARKAL database was developed to help local, state and regional decision makers to understand the environmental (climate and air quality) and health implications of energy supply and use in their regions, as well as the extent to which energy resources and technologies may contribute to achieving current and future environmental goals.

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