NYC Residential Emissions: Sources and Solutions

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Abstract

Analysis of New York City's greenhouse gas emissions data, collected from the five boroughs, determined that 68% of emissions come from buildings, and the largest proportion of these emissions, 31%, comes from residential buildings.The largest source of emissions within residential buildings is natural gas use, accounting for 58% of all residential building emissions, followed by electricity use, which accounts for 32%. Four solutions were proposed to mitigate residential emissions by targeting natural gas and electricity use in homes, either by reducing their consumption or decarbonizing their use: (1) energy efficiency upgrades, (2) heat pumps, (3) community solar, and (4) waste-to-energy biofuel production. Upgrading building energy efficiency was determined to be the most cost and carbon-effective method of reducing residential emissions because of existing technology and supply chain infrastructure. Implementing community solar and installing heat pump systems was determined to have moderate value, and developing waste-to-energy biofuel production was found to be a high-risk, high-reward solution.

Introduction

New York City has set a target of reducing greenhouse gas (GHG) emissions by 80% by 2050.[1] Reaching this ambitious target will require comprehensive plans to utilize solutions for many sectors. This study narrows its scope to study and design solutions for the sources that produce the highest emissions.

After examining datasets collected by NYSERDA and the NYC Mayor's Office of Climate and Environmental Justice, it was determined that residential buildings produce the highest emissions of greenhouse gasses in New York City (NYC). Four solutions were proposed and analyzed, using available data and/or case studies, to reduce residential emissions: energy efficiency upgrades, heat pumps, community solar, and waste-to-energy biofuel production.

Each solution was compared and categorized based on cost and benefit analysis to understand better which solution(s) are best suited for the largest number of individuals, buildings, and the environment and can be implemented as a preliminary mitigation strategy.

Keywords

Greenhouse Gas Emissions, Emissions Mitigation Strategies, New York City, Urban Climate Solutions, Residential Greenhouse Gas Emissions

Methods

1. Emissions Analysis

NYC's GHG Inventory is conducted annually through the Mayor's Office of Climate and Environmental Justice. The dataset following the

[1] NYC Climate Dashboard

Global Protocol for Cities (GPC) guidelines were analyzed using Excel for the years 2005 to 2021. This data is limited to within city limits and does not include fugitive emissions that occur outside of the city during transmission, distribution, and transportation into the city.[2] Fugitive emissions in residential buildings, or gas leaks, were not counted with other residential emissions but instead in their own category, including gas leaks across building types. This was done for accounting ease since the dataset reports it as its own aggregate category as well and because these emissions are relatively negligible compared to the total of other residential emissions. For comparison, fugitive emissions accounted for approximately less than 2 million metric tons of CO_2 equivalent (tCO_2e) emissions citywide, while electricity accounted for more than 15 million tCO_2e emissions in residential buildings alone.

2. Residential Building Energy Use Analysis

NYSERDA's Low-Carbon Retrofit Playbooks were used to estimate residential energy end uses. The playbooks provide strategies for retrofitting multifamily buildings and information about financial incentives from the Multifamily Buildings Low-Carbon Pathways Program. There are five playbooks, each for a different characteristic type of NYC residential building: 1-3 Story Garden Style, 4-7 Story Pre-War, 4-7 Story Post-War, 8+ Story Post-War, and 8+ Story Post-1980s. Each playbook is an in-depth case study to design a low-carbon retrofit of a specific and existing NYC building and includes data on their current energy cost, energy use, emissions, and systems design, as well as projected values that would result from various retrofits.[3] Energy use data was obtained by averaging values for each residence type.

NYSERDA chose the buildings studied as models to design retrofits for other NYC buildings and thus are assumed to be representative of typical buildings of their size and age. Although the playbooks are a minimal data size, they are very effective for the scope of this study and include more comprehensive information than the datasets available through local law reporting, which include far more buildings but are often incomplete and require great data cleaning efforts.

3. Solution Analysis

3.1. Energy Efficiency Upgrades

Cost and carbon benefit values were collected from the NYSERDA Playbooks and reported as a range over the five building types. For each building type, the estimated emissions mitigated were calculated using the playbook's estimate for the percent reduction in energy consumption as a result of envelope upgrades. This reduction was assumed to be in natural gas use because natural gas is most widely used for heating, and envelope upgrades reduce heating loads.[3] The emissions associated with natural gas use were calculated using the LL97 calculator, as was the cost of emitting over local cutoffs.[4]

Additionally, the cost and benefit analysis was done using the NYC Accelerator.[5] This reduction assumes the buildings were initially inefficient in all aspects of the envelope. Health and comfort benefits were also done using the NYC Accelerator.[5]

3.2. Heat Pumps

Carbon benefit in terms of emissions mitigated was calculated using NYSERDA Playbook values for the reduction in energy consumption associated with switching to a heat pump system. This reduction was assumed to be in natural gas usage, and emissions per kBTU of natural gas used were found using the LL97 calculator. Energy cost savings were also found in the playbooks, and savings associated with avoided emissions penalty fees were calculated using the LL97 calculator.

3.3. Community Solar

Cost and carbon benefits were analyzed using PowerMarket's online marketplace for community solar projects available to NYC residents. Each listing includes acreage, output capacity, maximum number of subscribers, percent energy bill savings, and annual GHG offsets.[6]

[2] NYC GHG Inventory
[3] NYSERDA Low-Carbon Retrofit Playbooks
[4] LL97 Emissions Penalty Calculator
[5] NYC Accelerator
[6] PowerMarket Marketplace

3.4. Waste-to-Energy Biofuel Production

Data on carbon benefits was collected from the EPA, the NYC Department of Environmental Protection, and Covanta, a waste-to-energy business. Additionally, cost benefits were determined from the sources mentioned above. Data generated from real-world applications as waste-to-energy biofuel production is implemented daily at Covanta, facilities in NYC, and across the nation, and more recently at WMNY's CORe facility and Newtown Creek WRRF in Brooklyn. Data for the facility in Brooklyn traced end to end on Veriflux, a platform funded by the EPA that provides end-to-end data on the waste-to-energy biofuel production process.

Results

1. Emissions Analysis

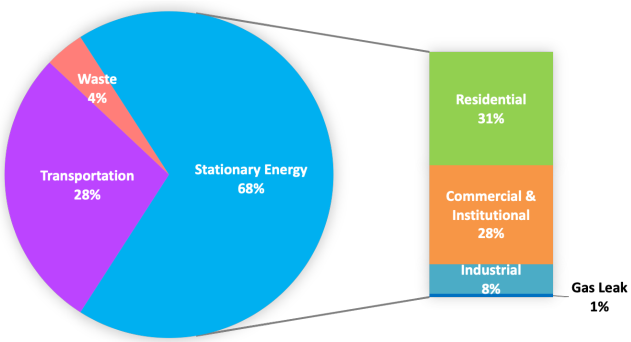

Figure 1: ***2021 Greenhouse Gas Emissions in NYC.*** Generated from GHG emissions data for each sector in tCO_2e. There are three predominant sectors that contribute to greenhouse gas emissions; stationary energy or buildings (68%), waste (4%), and transportation (28%). Of stationary energy, emissions sources are divided into residential (31%), industrial (8%), commercial and institutional (28%), and fugitive or gas leaks (1%).

Stationary energy, or buildings, is the largest source of GHG emissions in NYC, accounting for 68% in 2021. Of these emissions, 31% come from residential buildings, the largest proportion, and thus the focus of our study.

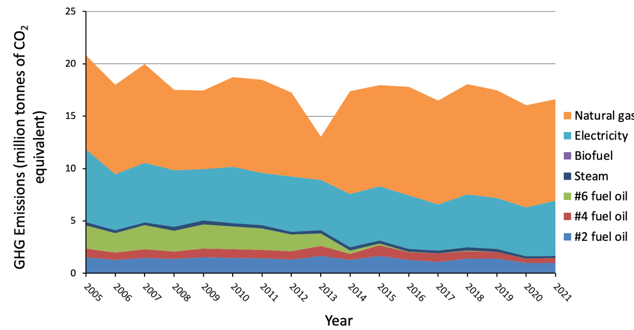

Figure 2: ***NYC Residential GHG Emissions by Source, 2005-2021.*** Generated from GHG emissions data for each source in tCO_2e. An explanation for the dip in 2013 could not be determined and may be an error in the reported data.

Analysis of residential emissions in NYC by source shows that natural gas accounts for a growing majority of emissions, followed by electricity as the next largest source. In 2021, natural gas use accounted for 58% of residential emissions, and electricity accounted for 32%. Fuel oils are slowly being phased out, and steam and biofuel have remained fairly constant and low-use. Therefore, strategies to mitigate residential building emissions must target natural gas use or electricity to reduce emissions effectively.

2. Residential Building Energy Use Analysis

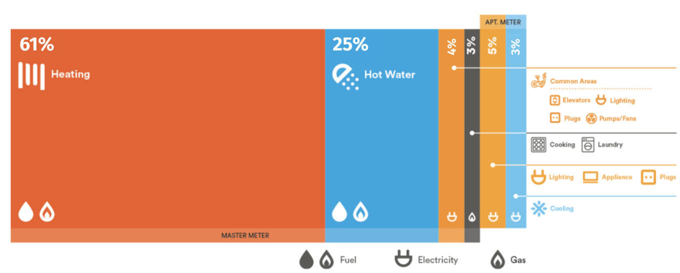

Figure 3: ***NYC Residential Building Energy End-Uses.*** Calculated by averaging values for each building type over 5 NYSERDA Playbooks.

Fuel oils and natural gas are used in NYC residential buildings for heating, hot water, and cooking, using approximately 61%, 25%, and 3% of total energy consumption, respectively. The other 12% is attributed to electricity used for appliances, lighting, and cooling.

3. Solution Analysis

3.1. Energy Efficiency Upgrades

a) Overview

This solution is the most technologically ready while also being the simplest to incorporate into existing buildings in NYC. According to NYSERDA, 80% of buildings across the state of New York were built before the implementation of energy codes, and they are currently emitting large amounts of avoidable emissions.[7] A plausible solution would be improving building envelope efficiency through window, wall, and roof insulation, and air tightness around ACs. These upgrades will reduce heat transfer to the outside, drastically reduce the energy consumed by heating and their associated emissions, and improve comfort in homes.

b) Policy and Tax Analysis

The Advanced Buildings Program promotes private investment and the advancement of the upcoming generation of cutting-edge building technologies. It allocates $18 million for the electrification and decarbonization of buildings by helping to fund building envelope systems and components, ground source heat pump cost compression, intelligent buildings, and thermal storage solutions for HVAC applications.[6]

The Comfort Home Program incentivizes energy efficiency upgrades with $1,000 to $4,000 for installation of seal and insulate packages, with this quantity depending on the choice to seal air leaks, make insulation upgrades for ceilings, floors, and walls, or installation of high-performance windows.[8]

Additionally, The Inflation Reduction Act also incentivizes clean, efficient energy solutions by offering significant federal income tax credits, available through 2032, and offers $600-$1200 for these strategies.[9]

Two of these three policies come from the state level, which is important as New York is one of the oldest states and requires a more local approach and holistic approach to upgrading its buildings. The assistance at a federal level is also necessary to help the expensive burden of such a big project. As this is the most cost-effective option for emissions mitigation, it is essential to have state and federal-level attention and aid in order to reduce emissions effectively, especially since so many could easily be avoided with this strategy implementation.

c) Cost and Carbon Benefits

While each strategy may have higher or lower costs and benefits individually, they are most efficient when implemented all together.[5]

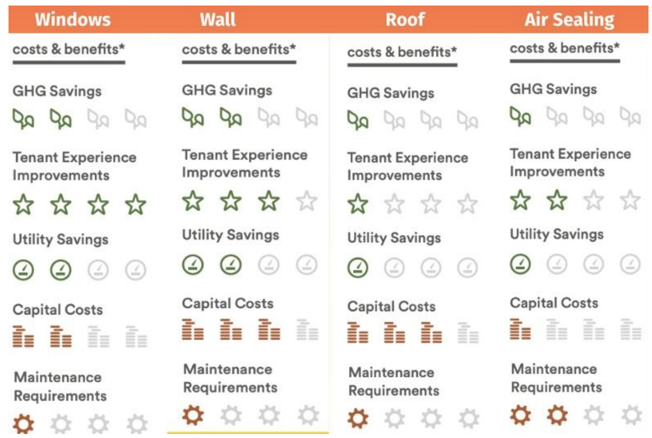

Figure 4: ***Envelope Improvement Costs & Benefits from New York City Accelerator and Building Energy Exchange.*** Cost and benefits of window, wall, and roof insulation and air sealing at room ACs, assuming all existing aspects of the envelope are minimally compliant. Ratings are determined by industry experts and calculated relative to the system end use, not the whole building.

With all these strategies combined on an inefficient building, this retrofit strategy would result in a 41-51% reduction in energy consumption, corresponding to 2-5 pounds of carbon dioxide equivalents mitigated per square foot per year. When applying these results to a typical-sized, 50,000 sq ft residential building, this would equate to 80 metric tons of carbon dioxide equivalents per year mitigated on average and $40,000 in savings per year on average from decreased energy costs and avoided emissions penalty fees.

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7 NYSERDA - Advanced Buildings Program

8 NYSERDA - Comfort Home Program

9 NYS Clean Heat

Table 1: ***Summary of Cost and Carbon Benefits for Residential Energy Efficiency Upgrades in NYC.*** Calculation for emissions mitigated was estimated using ~0.1 $lbCO_2e$ emitted/kBTU of natural gas used. Calculation for penalty fees was estimated using ~$250/$tCO_2e$ over limit. Both of these values found using LL97 calculator.

Residence Type	1-3 Garden	4-7 Pre-War	4-7 Post-War	8+ Post-War	8+ Post-80s
Reported Values					
% Energy Reduction	46%	51%	41%	42%	47%
% Total Energy for Heating	74%	60%	52%	56%	61%
Current Heating Demand (kBTU/sqft/yr)	33.59	58.4	43.55	48.24	45.41
Decrease in Energy Cost ($/sqft/yr)	0.49	0.41	0.25	0.39	0.49
Calculated Values					
Total Energy Consumption (kBTU/sqft/yr) = Current Heating Demand / % Energy for Heating	45.39	97.33	83.75	86.14	74.44
Energy Saved (kBTU/sqft/yr)	20.88	49.64	34.34	36.18	34.99
Emissions Mitigated (lbCO2e/sqft/yr)	2.08	4.95	3.42	3.60	3.49
Emission Penalties ($/sqft/yr)	0.24	0.56	0.39	0.41	0.40
Total Savings ($/sqft/yr)	0.73	0.97	0.64	0.80	0.89

d) Additional Benefits

Health, comfort, and building satisfaction would all increase with the implementation of these retrofit techniques. Improved building envelope and ventilation systems greatly improve indoor air quality, positively affecting health and reduces the risks of occupants developing respiratory infections and allergy symptoms.[10]

In addition to enhanced ventilation, improving health, implementing the retrofit strategies would also impact the home's thermal comfort and regulate the temperature much more effectively, reducing the effects of cold air leaking in during colder months.

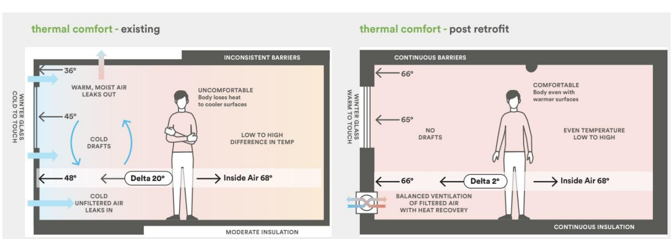

Figure 5: ***Building Energy Exchange.*** Impact of retrofit strategies on thermal comfort. An energy-efficient envelope ensures inside temperature remains warmer throughout the colder months and closer to the interior room temperature.

Cold air causes inflammation in the lungs and inhibits circulation, which increases the risk of respiratory conditions, such as infection, asthma symptoms or attacks, and can worsen chronic obstructive pulmonary disease (COPD).[11] In a post-retrofit home, there would be an even temperature that would keep the body at a comfortable temperature and would reduce the risk of cold air inflammation in the body. As a result of health and comfort benefits, tenants are presumed to be more satisfied in their home which can also correlate to satisfaction with the building they live in, and improving the relationship between landlord and tenant.

3.2. Heat Pumps

a) Overview

Heat Pumps are an electricity-powered combined heating and cooling system. They use the temperature difference between inside and outside air to transfer thermal energy in the desired direction via a circulating refrigerant. By transferring heat instead of generating it, they are far more efficient than a natural gas boiler, which is typical of NYC. They also allow for temperature control in individual rooms or units using a thermostat. This allows for far more energy efficiency than natural gas boiler systems that turn on or off-seasonally, regardless of the actual heating needs of the building.[12]

Several types of heat pumps are commercially available. Geothermal and air-source heat pumps are used for heating the air, and water heater heat pumps can be used for building hot water.[3] Each comes with unique costs and recommended applications based on building design, but for the purposes of this study, they are generally treated as a total heat pump system for both air and water.

b) Policy and Tax Analysis

The main policy promoting heat pumps is the NYS Clean Heat Initiative, which creates installation incentives through major utilities.[9] Consolidated Edison (ConEd), being the major utility in NYC, offers thousands in rebates depending on the type of heat pump installed, with even more incentives available for disadvantaged communities.[12] Federal

[10] PubMed - Ventilation Strategies to Reduce the Risk of Disease

[11] World Health Organization - Low Temperatures and Insulation

[12] ConEd - Heat Pumps for Renters and Homeowners

and state tax credits are also available for further incentives to switch.[9]

Table 1: ***Summary of Policy and Tax Incentives for Residential Heat Pump Installation in NYC.***

Heat Pump Type	Rebates	Tax Credit
Air-source	$5,000 - $10,000 per unit	Federal: 30% of cost, up to $2,000
Geothermal	$25,000 or $35,000 if in disadvantaged community	Federal: 30% of cost State: Federal: 25% of cost, up to $5,000
Water heater	$1,000	Federal: 30% of cost, up to $2,000

c) Cost and Carbon Benefits

Analysis of the NYSERDA Playbooks found that switching to a heat pump system reduced total energy consumption by 17% in 1-3 story garden style residences, and by 6% in the other residence types. This corresponds to mitigated GHG emissions of approximately 0.8 $lbCO_2e$/sqft/yr in garden-style buildings and around 0.5 $lbCO_2e$/sqft/yr in the rest.

Assuming that these avoided emissions brings a building under local cutoffs for emissions regulations, heat pump installation saves 5-9 cents/sqft/yr in avoided emission penalty fees. Combined with the playbook's reported values for energy cost savings associated with heat pump installation, around 4-6 cents/sqft/yr, the total saving is 10-15 cents/sqft/yr.

For a typical building of 50,000 sqft, installing a total heat pump system would result on average in 13 tCO_2e mitigated per year with savings of nearly $6,000.

Table 1: ***Summary of Cost and Carbon Benefits for Residential Heat Pump Installation in NYC.*** Calculation for emissions mitigated was estimated using ~0.1 $lbCO_2e$ emitted/kBTU of natural gas used. Calculation for penalty fees was estimated using ~$250/$tCO_2e$ over limit. Both of these values found using LL97 calculator.

Residence Type	1-3 Garden	4-7 Pre-War	4-7 Post-War	8+ Post-War	8+ Post-80s
Reported Values					
% Energy Reduction	17%	6%	6%	6%	6%
% Total Energy for Heating	74%	60%	52%	56%	61%
Current Heating Demand (kBTU/sqft/yr)	33.59	58.4	43.55	48.24	45.41
Decrease in Energy Cost ($/sqft/yr)	0.06	0.04	0.04	0.06	0.06
Calculated Values					
Total Energy Consumption (kBTU/sqft/yr) = Current Heating Demand / % Energy for Heating	45.39	97.33	83.75	86.14	74.44
Energy Saved (kBTU/sqft/yr)	7.72	5.84	5.03	5.17	4.47
Emissions Mitigated (lbCO2e/sqft/yr)	0.77	0.58	0.50	0.51	0.44
Emission Penalties ($/sqft/yr)	0.09	0.07	0.06	0.06	0.05
Total Savings ($/sqft/yr)	0.15	0.11	0.10	0.12	0.11

3.3. Community Solar

a) Overview

Community solar provides carbon-neutral electricity to renters, homeowners, and low-income residents. Community solar works to decarbonize the entire electrical grid, through the distribution of clean electricity, funded by residents. Community solar refers to a solar farm that allows customers within a given geographic region to "subscribe" to the farm without needing to install solar panels on their own roofs. Customers benefit from solar power offsite. Each customer receives a solar credit on their typical electric bill for the amount of solar that their share of that farm produced that month, saving the subscriber 10-15%.[13] Because the electricity produced is connected to the local grid, it reduces the grid's dependence on fossil fuels.

This solution allows New York City residents, one-third of whom rent[14], to participate in solar, independent of their living situation. As long as they pay an electrical bill, a resident can participate. This allows low-income residents who otherwise could not afford the high costs of solar to participate in clean energy and even save money. This significantly increases solar's capacity, eliminating the financial barrier.

[13] Dept of Energy - Community Solar Basics

[14] NYU Furman Center - State of Renters and Their Homes

b) Policy and Tax Analysis

Community Solar developers like Consolidated Edison and smaller developers like EmPower receive the tax benefits provided by the Inflation Reduction Act. The Inflation Reduction Act provides a 30% tax credit to all community solar developers on the costs of their project. The Inflation Reduction Act has provided 7 billion dollars in additional funding for community solar farm development, specifically through the Greenhouse Gas Reduction Fund. The 7 billion dollar fund is managed and distributed by the Environmental Protection Agency (EPA).[15]

Looking at the customer side, customers receive one monthly bill, combining community solar benefits and their typical electric bill. This is made possible through New York State's single bill solution, Net Crediting[16]. This process waives the typical Community Solar fee and makes the process of switching to Community Solar seamless and inviting for all residents.

c) Cost and Carbon Benefits

A subscriber of community solar saves an average of 10-15% per month on their electric bill. Farms tend to be 10-20 acres, with each acre offsetting approximately 130 tCO_2e annually.[6] For an average farm of 15 acres, 2,000 tCO_2e are mitigated each year.

A local example is the Pink Houses Solar Farm in Brooklyn, located across the rooftops of a public housing complex. The farm has a 910 kW capacity available for 137 subscribing households, with each household offsetting 6 tCO_2e annually.[6] The energy bill savings could directly benefit the low-income residents of the housing complex if they choose to subscribe.

3.4. Waste-to-Energy Biofuel Production

a) Overview

Waste-to-energy biofuel production is a method of waste disposal that can be used to reduce greenhouse gas production by redirecting waste from landfills.

This method of energy production generates energy by processing municipal solid waste remaining after recycling, producing electricity and useful byproducts.

There are currently 75 facilities in the US that utilize the waste-to-energy fuel production method.[17] Energy recovery is less common than combustion because of access to land. Suburban, rural, and urban regions have varying population densities, and as a result varying amounts of land reserved for development. In the past, waste-to-energy methods have faced opposition because of the lack of policy and restrictions on air pollution, and potential residential congestion as a result of facility industrialization. Lastly, the cost for the creation of a facility is not cheap, and the challenge is getting stakeholders to understand the return on investment for both the environment and community.

Despite these economic and social barriers, two local businesses are implementing waste-to-energy fuel production. Covanta, a waste-to-energy company with locations throughout the country, utilizes waste collected by the NYC department of sanitation, and through marine transportation, transports it to Queens and produces energy and recovers metal through combustion. Additionally, Waste Management of New York and the New York City Department of Environmental Protection created a waste-to-energy supply chain, processing the food waste at WMNY's CORe facility then transporting an engineering bioslurry to Newtown Creek WRRF for co-digestion. Veriflux, an EPA based technology, is used to track the waste recovery process to determine weak and strong points in the supply chain.

Waste-to-energy recovery methods utilize a circular economy based approach to fuel production through the repurposing of municipal solid waste. Additionally, there are benefits throughout the supply chain that can generate carbon offsets for residents and businesses, providing incentives for the consumer and mediation for the environment.

b) Policy and Tax Analysis

In 2005, the Energy Policy Act, Renewable Fuel Standard, was created to introduce economic incentives for utilizing and developing technology

[15] EPA - Initial Program Design of Greenhouse Gas Reduction Fund

[16] NYSERDA - Community Solar for Contractors

[17] EPA - Energy Recovery from Combustion of Municipal Solid Waste

that would allow for the blending of renewable fuels with gasoline. Benefits such as grants, income tax credits, subsidies, and loans were awarded to promote research and development of renewable technologies. Additionally, the Renewable Fuel Standard mandated the blending of 7.5 billion gallons of renewable fuels by 2012.[18]

The Energy Independence and Security Act of 2007 (EISA) was created, and expanded on the Renewable Fuel Standard. This new policy increased biofuel production to 36 billion gallons by 2022. In addition to production, funding was allocated for the creation of infrastructure for biorefineries and commercial applications, which utilize cellulosic fuels.[18]

Numerous acts and policies supporting biofuel production have been created. More recently, the Inflation Reduction Act was created to provide funding for research and development of emerging sustainable energy technologies that are beneficial to both the consumer and the environment.[19]

In the past, acts were created to help fund research into energy solutions, but more recently, policies have been instituted to support the growth of infrastructure needed to implement sustainable energy storage and production methods on an industrial scale.

c) Cost and Carbon Benefits

Waste-to-energy biofuel production has carbon benefits because it can be used to reduce the lifecycle of greenhouse gas emissions.

At Covanta, for every ton of solid waste converted into energy, up to 1 ton of carbon dioxide is offset. Within a year, over 100 million tons of carbon dioxide would be offset, given that waste is being redirected from landfills and used instead for energy production. Additionally, the material combusted is what remains after recycling, further reducing the volume of waste. After combustion, remaining ash is processed for metal collection, which is recycled for other uses, reducing the need for resource extraction. The amount of energy generated from the waste-to-energy conversion method provides energy to 46,000 homes around NYC, and collects enough metal to create 21,000 cars.[19] This method of fuel production can generate carbon benefits for the consumer but also directly for the environment, given that emissions from transportation, energy generation, and landfills are reduced.

In 2022, the Newtown Creek Wastewater Resource Recovery Facility, Veriflux, and the Waste Management of New York applied for the EPA Small Business Innovation Research Phase 1 Program to trace and optimize the waste-to-energy process. Over the course of the pilot program for this project, 1,750 tons of organic waste from approximately 600 restaurants, cafeterias, public waste bins were collected and sent to the Waste Management's CORe plant for processing, turning the waste into a feedstock, engineering bio-slurry (EBS), used for downstream production of fuel at the Newtown Creek Wastewater Resource Recovery Facility. During this project 100 truckloads contained 3.5 million pounds of waste in grease traps and food forms. From this collection, the pilot program produced energy for approximately 5,200 homes, and reduced annual greenhouse gas emissions by more than 90,000 metric tons. The equivalent to this would be reducing drivable cars by 19,000 or forwarding 1.5 million trees for 10 years, detailing the speed at which carbon can be offset through this method of fuel production.[20,21]

Although infrastructure may need to be built for the implementation of the waste-to-energy conversion methods, marginal land use is needed. All of the resources needed to create energy do not need to be extracted and can actually reduce the amount of land needed for production, as the volume of waste at landfills is being reduced. Additionally, reliance on global and domestic fuel exporters is reduced given that energy can be produced in the same region in which the resources needed for production are found. Socially, this increases energy security and autonomy for local communities and governments.

Fuels produced using the waste to energy method can be used to fuel homes, but additional byproducts

[18] EPA - Economics of Biofuels
[19] Covanta - Waste to Energy
[20] EPA - Food Scraps to Fuel
[21] New York City - Wastewater to Renewable Energy

of combustion can be used to create products such as cars and gas needed for other supply chains and manufacturing methods. Regarding carbon benefits, these three streams reduce greenhouse gas emissions given that products are collected at every step, rather than disposed of or wasted. Cost is most important to Covanta given that they are producing the energy. By limiting the supply chain to NYC, the cost of transportation and resource collection is significantly reduced, ultimately reducing the cost for the consumer and landlords.

Discussion

Residential buildings were identified as a critical source of GHG emissions to target in NYC. Residential emissions largely come from natural gas use, which is primarily used for heating in homes, followed by electricity use.

To mitigate these emissions, four solutions were proposed that target different areas of the problem. Energy efficiency upgrades drastically reduce natural gas use by making heating more efficient. Heat pump installation electrifies the heating system, reducing natural gas use and allowing for future emissions mitigation by sourcing clean electricity. Community solar decarbonizes grid electricity by shifting its source towards solar. Waste-to-energy biofuel decarbonizes fuel use and electricity generation.

No one solution will mitigate residential emissions fully, but not all should be pursued equally. Energy efficiency upgrades are the highest priority as they have the greatest emission mitigation to cost value. They can reduce a residential building's energy consumption by up to 50% while being fairly easy to install through utilizing existing and competitive technology, policy and tax incentives, and tenant support because of their benefits for resident comfort and health.

Community solar is of similarly high emission mitigation to cost value, but lower priority as it decarbonizes electricity, which accounts for a smaller share of residential emissions than natural gas. Community solar can completely mitigate a home's electricity use and saves money for the resident. Capital costs of farm production are usually borne by a larger energy company, heavily subsidized, and often from farms outside of the city limits. However, since space in and around NYC is very limited, and building up solar in other areas but restricting benefits to NYC may run into political roadblocks, the overall capacity for community solar may be limited.

Heat pumps have moderate carbon to cost value. They require greater system overhaul and capital costs to residents and building owners than energy efficiency upgrades or community solar. However, they will be necessary for future emissions mitigation in residential buildings because they decommission natural gas use and completely electrify building heat systems. As the grid increasingly becomes powered by clean energy sources, heat pumps will become as clean as their electricity source, enabling the net-zero targets that the city has set. This makes heat pumps a necessary technology that buildings must switch to, but one of lower priority at the moment.

Finally, waste-to-energy biofuel production is of marginal carbon to cost value. This is due to the capital costs associated with scaling up biofuel operations in NYC, which would involve expanding plant construction and landfill waste shipping to the plants. This solution also has less developed technology than others covered, so a large volume of the political and economic incentives for biofuel are for its research and development rather than for infrastructure and implementation. However, this solution has incredible capacity to reduce emissions across many sectors, from fuel and electricity in buildings and transportation to landfill waste emissions, and would drastically change NYC's overall emissions and municipal systems if implemented on a large scale.

It is important to note that the solutions we have proposed could also be adapted for commercial and institutional buildings, the second largest emitter of NYC's stationary energy behind residential buildings. Re-evaluating how these solutions stack up when applied to commercial buildings is a critical next step to address further areas of NYC emissions and to continue to design mitigation strategies to reach net-zero goals.

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