NEW YORK CITY HOUSEHOLD CONSUMPTION-BASED EMISSIONS INVENTORY

2019 Base Year

Prepared February 2023

EcoDataLab

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Introduction

This household consumption-based emissions inventory (or "CBEI") for New York City is an estimate of the greenhouse gas (GHG) emissions associated with the consumer spending activity of New York City residents in 2019. The inventory is produced by EcoDataLab with contribution by C40 Cities and feedback from New York City staff, made possible by the financial support of American Express.

A household CBEI is a supplement to the standard geographic or territorial GHG inventory that cities use to estimate emissions occurring within a city boundary and that form the basis of most cities' climate action plans. By comparison, the majority of the emissions estimated in a CBEI occur outside a city's boundary, though it also includes some emissions already counted in the city's existing territorial inventory. The two inventories are created using different methods and data sources, providing different views of emissions impacts. Some emissions induced by the city are not captured in either inventory, such as the impacts of business or tourism consumption.

New York City's territorial inventory estimates production-based emissions that occur in the city in three sectors: energy and buildings, transportation, and waste.

Calculated using the Global Protocol for Community-scale Greenhouse Gas Inventories (GPC), it relies on local activity data such as actual units sold (e.g. MWh of utility energy, gallons of diesel fuel); models of transportation flows (e.g. vehicle-mile-traveled by mode); and calculations of emissions from landfills, power, water, and manufacturing facilities in or used by the city.

As outlined in the methodology section (Appendix 1) of this report, the CBEI uses national spending, demographic, economic trade, and local energy data to model the emissions generated by the annual consumption patterns of an average household. Emissions are reported by consumption category (food, goods, services, etc.) rather than emissions source category. This inventory has been created for 2019 because that is the most recent robust consumer expenditure dataset available unaffected by the COVID-19 pandemic.

A CBEI estimates lifecycle emissions, which means that it seeks to calculate the emissions created by producing, transporting and selling a product, regardless of where in the world those emissions are generated. These are often called embodied or embedded emissions. For a simplified example, consider a household appliance that may be assembled in one place from parts produced in another and sold and used in a third and fourth place. In a CBEI, those emissions would all be included in the 'goods' category for the city in which the ultimate purchaser resides.

New York City's household CBEI consist of GHG emissions associated with household activities in the following categories:

- The **food category** includes food consumed at home by residents of New York, categorized by meat, dairy, fruits & vegetables, and other foods. This category also includes emissions from expenditures at food service venues (such as restaurants, fast food places, etc.) in a sub-category called eating out.
- The **goods category** includes all products purchased by households, such as furniture, clothing, electronics, and personal care products (excludes items accounted for in other categories, such as food and fuel).
- The **housing category** includes household energy use, home construction and maintenance (shelter), and water.
- The **private transportation category** includes on-road vehicle travel, vehicle purchases, maintenance, and flights.
- The **services category** includes services used by households such as healthcare, education, insurance & finance, and entertainment experiences like concerts and museums.

Findings

In New York City, the total GHG emissions associated with consumption in households (measured in metric tons of CO_2e, or $MTCO_2$e) is calculated to be 92 million $MTCO_2$e in 2019. With 3,211,033 households, a typical household was responsible for roughly 29 $MTCO_2$e annually, or about 11 $MTCO_2$e per person.

- New York City's average household is responsible for only about two-thirds of the average emissions of a typical U.S. household, as the national average is 43 $MTCO_2$e per household per year or 17 $MTCO_2$e per person. New York's variation is likely due to population and employment density, higher usage of public transit, and smaller, more energy-efficient homes.
- Food is the leading source of household emissions in New York City, responsible for 25% of total residential consumption emissions. Within the food category, eating out and animal products (including meat, dairy, fish, & eggs) are the largest sources, accounting for nearly half of all food emissions.
- Housing and services are the next two biggest contributors for household consumption emissions in New York City, and private transportation is the lowest category. This profile differs from the national average and other more car-dependent cities in which private transportation is often the largest category.
- Consumption emissions in New York City vary significantly across neighborhoods, with up to a 3-fold difference in areas across the city. This variation is due to socioeconomic differences including household income, which is one of six characteristics used in the CBEI model.

Emissions by Category

The bar chart in Figure 1 provides an overview of the city's average per-household emissions in 2019. Actual emissions of any particular household could vary significantly from this average due to differences in household size, spending, housing, travel, and other discretionary and non-discretionary factors.

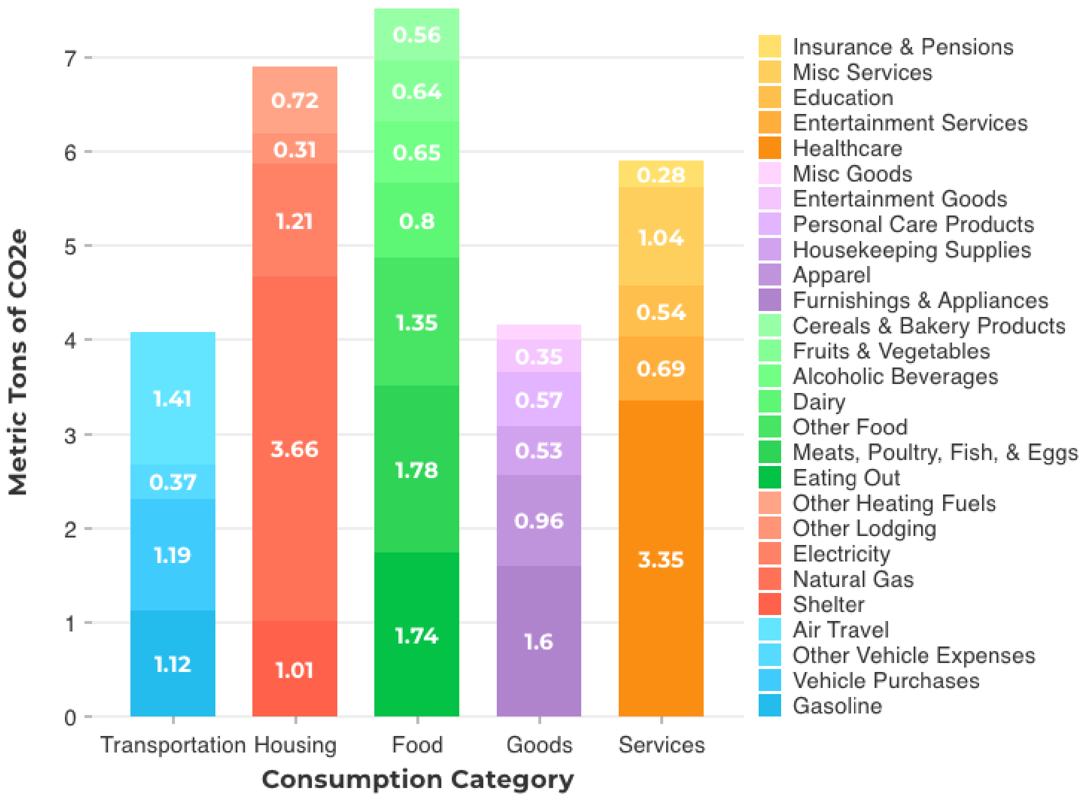

Figure 1. New York City Average Household Consumption-Based Emissions 2019

Food

Food accounts for 7.5 $MTCO_2e$ per household. The two largest sub-categories are eating out and meats, poultry, fish, and eggs, each at about 1.8 tons, or 23% of total food emissions.

Food sub-categories such as meat, dairy, fruits & vegetables refer to food consumed at home. Eating out refers to food prepared and served outside the home.

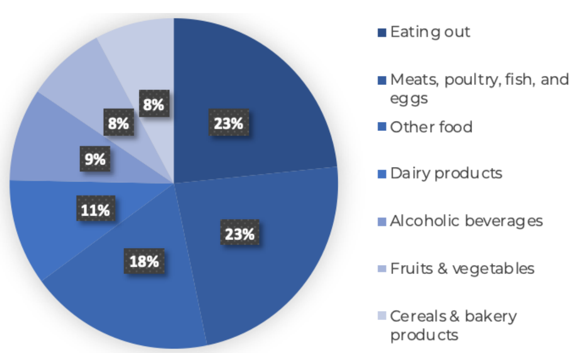

Figure 2. New York City Food Emissions Breakdown

Sub-categories:

- Eating out refers to any food prepared and served outside the home at restaurants, bars and hotels and even at workplaces, schools etc. and also the operational emissions from restaurants, including cooking, transportation, and construction of the building. In comparison, household emissions from cooking are allocated to the transportation and housing sectors.

- All other sub-categories in food include emissions associated with the production, freight transportation and sale of food for home consumption. These emissions do not include those created when cooking the food, transporting it home or other household emissions.

Housing

A typical New York household has 7.0 tons of GHGs resulting from housing, with the largest single category being use of natural gas.

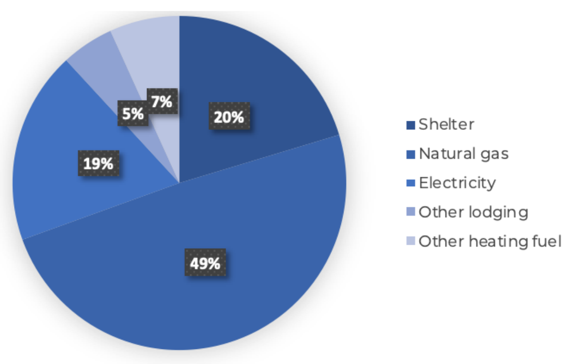

Figure 3. New York City Housing Emissions Breakdown

Sub-categories:

- Shelter includes emissions associated with home construction (amortized over the lifetime of the building), financing and insurance, maintenance and repairs, and water use in owned and rented buildings

- Natural gas includes emissions from home heating, water heating, clothes drying, and cooking (mainly home heating).

- Electricity emissions derive from general household usage of appliances, lighting, electronics, etc. Some electricity emissions also derive from heating.

- Other lodging includes hotels, motels, and other group housing or vacation accommodations in which residents of the city stay when traveling, including both the emissions associated with electricity & heating, as well as construction, maintenance, and financing of other housing.

- Other heating fuel includes fuel oil, steam, and propane.

Private Transportation

For an average household in New York, private transportation accounts for 4.1 $MTCO_2e$ per year, per household. Much of this comes from air travel, which accounts for 1.4 tons, or 34% of the total transportation emissions.

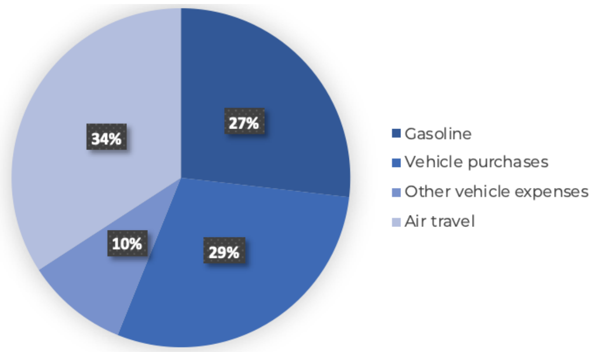

Figure 4. New York City Transportation Emissions Breakdown

This category does not include public transit within or between cities and it does not include use of taxis or car share services. These popular modes of transportation in New York City are calculated in the GPC geographic inventory.

In this inventory, public transit is in the government category of emissions discussed later in this report because transit fares paid by consumers are a small fraction of funds spent on U.S. transit, which is primarily a public infrastructure expense.

Sub-categories:

- Air travel is emissions associated with all personal air travel, anywhere in the world, including both direct and indirect emissions (such as fuel refining emissions and additional global warming effects from high-altitude pollution). Business travel is incorporated into emissions from other sectors.
- Gasoline emissions are associated with the use of personal automobiles (not business or paid automobile travel, like taxis) and they are estimated using the EcoDataLab VMT model described in the methodology appendix. This category includes expenditure on all vehicle fuels, as well as the upstream (e.g. refining and extraction) emissions associated with producing these fuels.
- This inventory assumes US national average fuel economy, but future updates are expected to include New York-specific fuel economy data.
- Vehicle purchases include all emissions associated with the production, manufacture, and purchase of vehicles. While this is primarily cars and trucks, it also includes vehicles such as motorcycles, RVs, boats, and pleasure aircraft.
- Other vehicle expenses include maintenance & repairs, accessories, insurance, and rentals.

Goods

Goods account for 4.2 $MTCO_2e$ per household per year. Of these goods, furnishings & appliances is the single largest source, making up 1.6 tons, or 38%, of total goods.

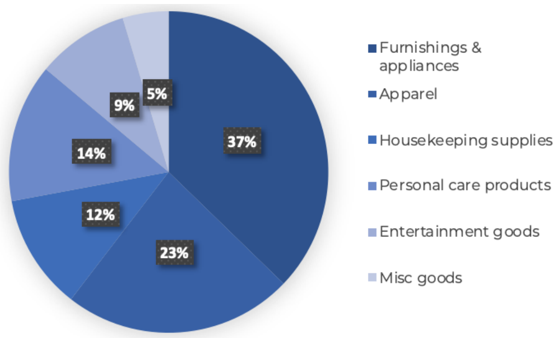

Figure 5. New York City Goods Emissions Breakdown

Sub-categories:

- The specific subcategories for goods include all emissions associated with the production, transportation and sale of those goods.
- Furnishings & appliances includes furniture, appliances, carpets, decor, lighting, computers & software, gardening supplies, kitchenware, etc.
- Apparel includes all clothing for adults and children.
- Housekeeping supplies include cleaning products, paper products, some linens, etc.
- Personal care products include soaps, toiletries, cosmetics, and other grooming supplies.
- Entertainment products include audio and visual equipment and products (e.g. TVs, speakers, etc.; video streaming, rentals, purchases [digital or physical], etc.), musical instruments, photography equipment, games, hobbies, bicycles, pets, sporting goods, etc.
- Miscellaneous goods include books and tobacco material.

Services

Services account for 5.9 $MTCO_2e$ per household. Healthcare is the largest category at 3.4 tons, or 57%.

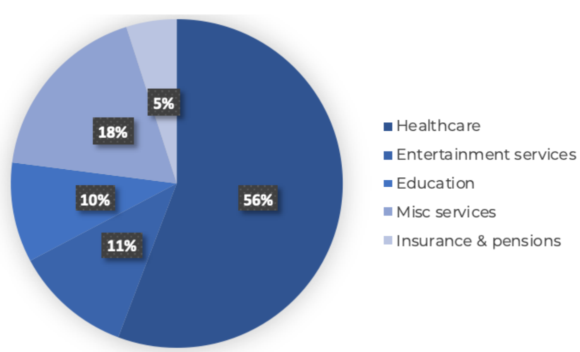

Figure 6. New York City Services Emissions Breakdown

Sub-categories:

- Healthcare includes emissions associated with hospitals, doctor & dental offices, nursing facilities, outpatient care, ambulatory services, and other medical establishments and services, including the associated construction, electricity, and heating emissions for those facilities, along with all emissions related to the production of associated medical devices and medications purchased by those facilities.
- Entertainment services include fees & admissions to museums, concerts, sporting events, performing arts, amusement parks, campgrounds, gyms, and movie theaters.
- Education includes elementary and secondary schools and higher education (including community colleges, colleges, universities, and professional or vocational schools).
- Miscellaneous services include things like personal care services, household operations (including childcare, laundry, moving, and repair services), cash contributions (religious & community institutions), and miscellaneous services (like banking, tax preparation, funerary arrangements, etc.).
- Insurance and pensions include life insurance, pension funds, and financial investment services.

Emission Comparisons

Household GHG Emissions over Time

Figure 7 illustrates New York City's household emissions from 2007 to 2019. The calculations show that the emissions have declined by 7.7% from 2007 to 2019. Some of this variation is due to changes in spending habits in categories and some is due to reduced emissions intensity. For example, emissions from vehicle miles traveled have reduced over the years likely due to improved fuel economy and emissions reductions in electricity are likely due to lower carbon intensity of the grid.

Figure 7. New York City's household GHG emissions over time (2007-2019)

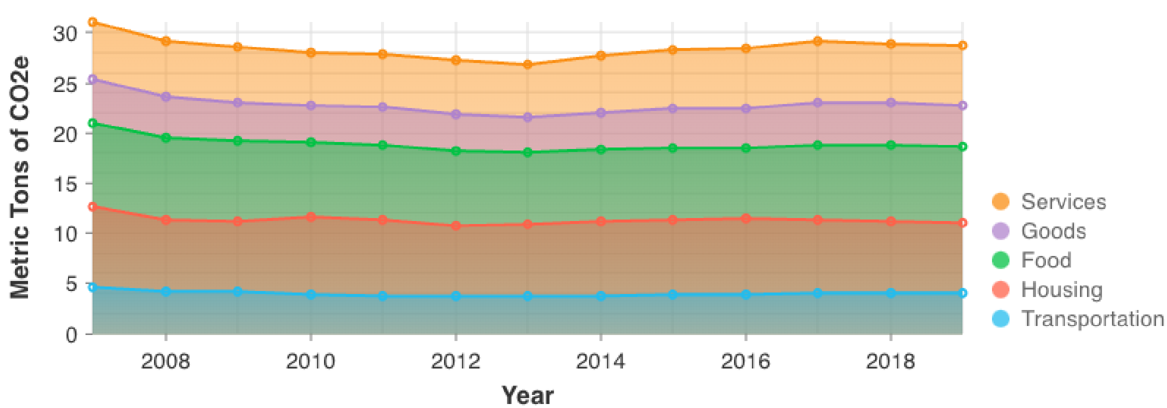

Table 1 below shows the level of all categories and sub-categories in 2007, 2012, 2017, 2018 and 2019.

	New York Average Household Emissions ($MTCO_2e$)				
Category	**2007**	**2012**	**2017**	**2018**	**2019**
Transportation Total	4.7	3.8	4.1	3.9	4.1
Gasoline/Vehicle miles traveled	1.7	1.3	1.2	1.2	1.1
Vehicle purchases	1.0	0.9	1.1	1.1	1.2
Other vehicle expenses	0.4	0.3	0.3	0.3	0.4
Air travel	1.5	1.2	1.4	1.4	1.4
Housing Total	8.0	7.0	7.2	7.3	7.0
Shelter	1.3	1.1	1.1	1.0	1.0
Natural gas	3.5	3.0	3.6	3.8	3.7
Electricity	1.4	1.5	1.4	1.4	1.2
Other lodging	0.3	0.3	0.3	0.3	0.3
Other heating fuel	1.4	1.1	0.8	0.8	0.7
Food Total	8.3	7.3	7.6	7.5	7.5
Eating out	2.1	1.7	1.8	1.8	1.7
Meats, poultry, fish, and eggs	2.1	1.8	1.8	1.8	1.8
Other food	1.4	1.2	1.3	1.3	1.4
Dairy products	0.9	0.8	0.8	0.8	0.8
Alcoholic beverages	0.7	0.6	0.7	0.7	0.7
Fruits & vegetables	0.6	0.6	0.6	0.6	0.6
Cereals & bakery products	0.6	0.6	0.6	0.6	0.6
Goods Total	4.4	3.7	4.2	4.2	4.2
Furnishings & appliances	1.5	1.2	1.6	1.6	1.6
Apparel	1.2	0.9	1.0	1.0	1.0
Housekeeping supplies	0.6	0.5	0.6	0.5	0.5
Personal care products	0.5	0.5	0.6	0.6	0.6
Entertainment goods	0.4	0.4	0.4	0.4	0.3
Misc goods	0.3	0.2	0.2	0.2	0.1
Services Total	5.7	5.4	6.1	5.9	5.9
Healthcare	3.0	3.0	3.4	3.3	3.3
Entertainment services	0.6	0.5	0.6	0.6	0.7
Education	0.6	0.6	0.6	0.5	0.5
Misc services	1.2	1.1	1.2	1.2	1.0
Insurance & pensions	0.2	0.2	0.3	0.3	0.3
Total Emissions	**31**	**27**	**29**	**29**	**29**

Table 1. 2007, 2012, 2017, 2018, and 2019 New York City Consumption-Based Emissions (MTCO2e per household)

Comparing New York City and U.S. Average

The following table compares the New York City average household emissions with those of the US average.

Category	New York (2019)	US (2019)
Transportation	4.1	13.6
Housing	7.0	8.4
Food	7.5	8.2
Goods	4.2	4.9
Services	5.9	7.8
Total	29	43

Table 2. 2019 New York City vs US Consumption-Based Emissions (MTCO2e per household, 2019)

Variation in Household Emissions by Borough and Census Tract

New York City neighborhoods have substantial variations in both emissions and the key driving demographic variables. The highest-emitting census tract has per-household emissions of 58 tons, while households in the lowest-emitting tract have emissions of 18 $MTCO_2e$ - roughly a 3-fold difference.

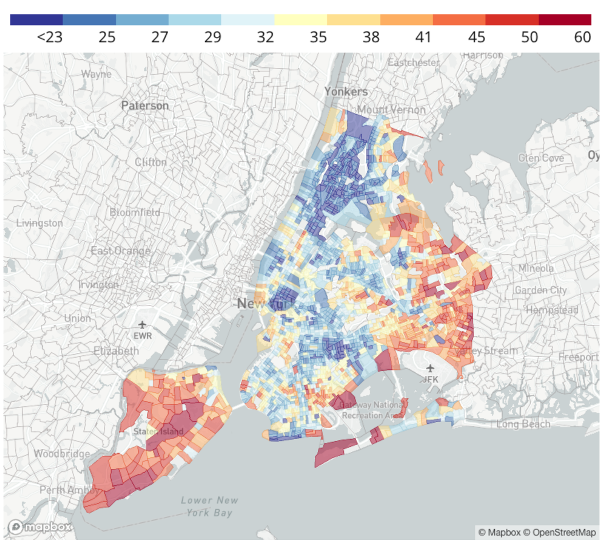

Figure 8. Consumption-Based Emissions Map ($MTCO_2e$ per household)

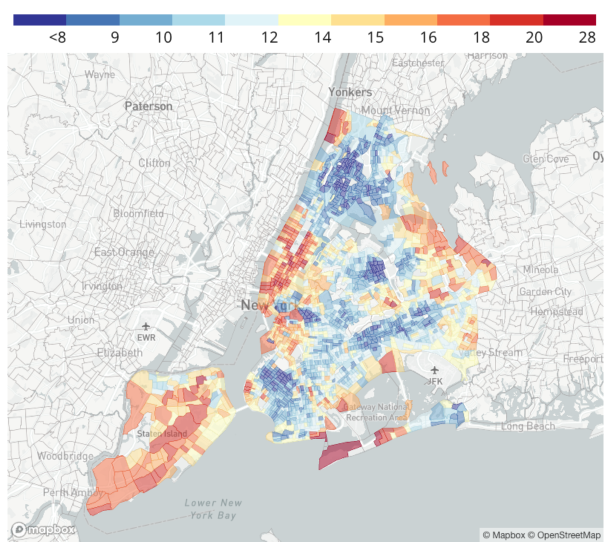

Figure 9. Consumption-Based Emissions Map (MTCO2e per person)

Table 4 below compares New York City's five boroughs and their associated consumption-based emissions (CBE). All emissions are per household for 2019.

Category	Bronx	Brooklyn	Manhattan	Queens	Staten Island	NYC Average
Transportation Emissions	2.5	3.2	3.7	7.0	12.3	4.1
Housing Emissions	6.0	7.1	6.0	7.7	9.1	7.0
Food Emissions	6.9	7.5	7.3	8.0	8.5	7.5
Goods Emissions	3.6	4.1	4.2	4.4	4.9	4.2
Services Emissions	4.9	5.8	6.0	6.3	7.6	5.9
Total Per Household Emissions	24	28	27	33	42	29
Total Per Capita Emissions	9	11	13	12	15	11

Table 4. New York City Borough Emissions Comparison

Model for Calculating Consumption-based GHG Emissions

A household CBEI is an estimate of the GHG emissions associated with the activity of all residents of a geographic area. Emissions that derive from consumption can occur anywhere in the world, and therefore it is virtually impossible to measure and attribute them directly, and instead, these emissions are estimated.

EcoDataLab uses a model (a series of complex calculations) to estimate consumption and emissions, using a combination of real-world consumption or emissions data along with predictions based upon household characteristics and regional and national averages.

The model used for this CBEI is based on six key household characteristics that are used to scale national-level household expenditure data. These household characteristics are:

- Household size
- Household income
- Vehicle ownership
- Home size
- Educational attainment
- Home ownership[1]

[1] In addition, supplemental models for household energy use and vehicle miles traveled incorporate additional variables such as local climate, energy prices, home type, and geographic region, for the energy model; and time to work, commute mode, density, and family status for the vehicle miles traveled model. For a full list of variables used in each model, see Appendix A. Methodology.

These variables are selected because they are demonstrated to have clear, direct effects on consumption. For instance, larger homes generally take more energy to heat or cool, while more people per household also means more food consumed per household. These variables are also available nationwide through US Census data, allowing for detailed local analysis at a range of geographic scales.

The emissions profile for New York City is based on an average household in 2019 (the most recent robust dataset available for this project without impacts from the COVID-19 pandemic). Known changes in emissions after 2019 are not included. For example, it is now known that emissions from electricity went up in 2020, due to the closing of the Indian Point Energy Center and transition from nuclear energy to other sources. This change in electricity emissions is not reflected in this inventory.

Unlike other CBEI approaches that scale solely on household income, this model allows for some ability to see the effect of policy and to track changes over time by including the six characteristics. The inventory also includes local data and emissions intensity for energy and water consumption. However, local changes in policy, behavior, infrastructure, and technology that might affect consumption or emissions in ways beyond the model variables are not included. For instance, if a local policy changed consumption patterns or the carbon intensity of products or services consumed by residents, this model cannot monitor those changes with the current methodology. For more details on the CBEI model, see Appendix 1. Methodology.

Using this CBEI with the Territorial Greenhouse Gas Inventory

New York City's territorial GHG inventory includes emissions that occur locally due to activities taking place within the geographic boundary of the city. In 2019, New York City estimated 55 million MTCO_2e in its territorial inventory,[2] dominated by building energy use, at 37 million MTCO_2e, comprising over 68% of the total emissions. Of the remainder, transportation accounted for about 16 million MTCO_2e, just shy of 29% of the total, and waste made up about 2 million MTCO_2e, or about 4%.

In contrast, the CBEI estimated a total of 92 million MTCO_2e, about 67% more than in the territorial inventory. In the CBEI, on-road private transportation is only 4% of emissions, while building energy is about 19% of household emissions. The CBEI only considers transportation and building energy emissions directly from residents. Commercial and industrial energy activity is factored in business sector categories, but the method does not calculate energy use in non-residential buildings. Goods and services that are consumed by people living outside of New York City are not included in the CBEI, even if they are produced or procured within city boundaries.

This disparity between the territorial inventory and CBEIs is common for large US cities. A CBEI that is much larger than a territorial inventory indicates that New York City is a net exporter of emissions, which is to say the residents of the city induce more emissions elsewhere in the world from goods and services they consume than the city produces locally.

[2] https://nyc-ghg-inventory.cusp.nyu.edu/

Appendix 1: Methodology

EcoDataLab CBEI Modeling Approach Overview

An inventory of consumption emissions is not a direct measurement of an individual resident's consumption or behavior. Instead, EcoDataLab uses a model (a series of complex calculations) to estimate consumption and emissions attributable to the lifestyles of residents of a city, using a combination of real-world consumption or emissions data where available, along with predictions based upon household characteristics, as well as regional and national averages.

This model is based upon an approach first developed by the CoolClimate Network at the University of California, Berkeley, and published extensively in multiple scientific journals.

The overall model has a number of sub-models, but each one follows the same general formula:

1) Select a survey
We select a nationwide survey, conducted by the US federal government, that focuses on an important element of the inventory. The US sub-models are built using the Consumer Expenditures Survey (CEX), the National Household Travel Survey (NHTS), and the Residential Energy Consumption Survey (RECS).

These surveys are used to build the full suite of models. CEX provides data used to model all categories of consumption except for gasoline and home energy use. NHTS provides data for the vehicle miles traveled model (which translates into gasoline usage), and RECS provides data for the home energy use models (including electricity, natural gas, and other heating fuels).

2) Identify key household characteristics
Next, we look at the household characteristics available from the survey and identify data for which we can get nationwide data from the US census and other data sources. These data include variables like household size, income, vehicle ownership, etc. We also include geography, climate, and other relevant data where applicable. See figure 11-16.

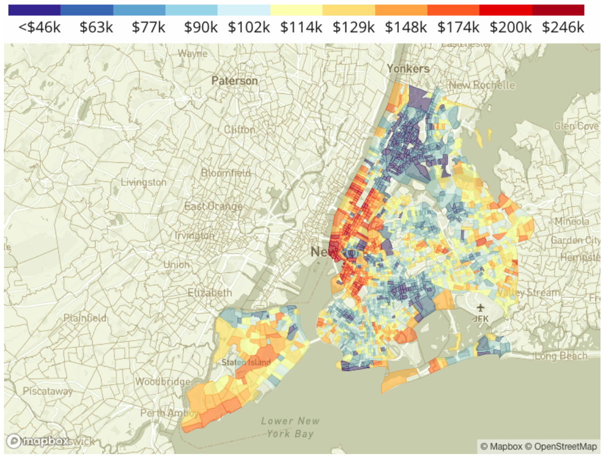

Figure 10. Average Household Income ($)

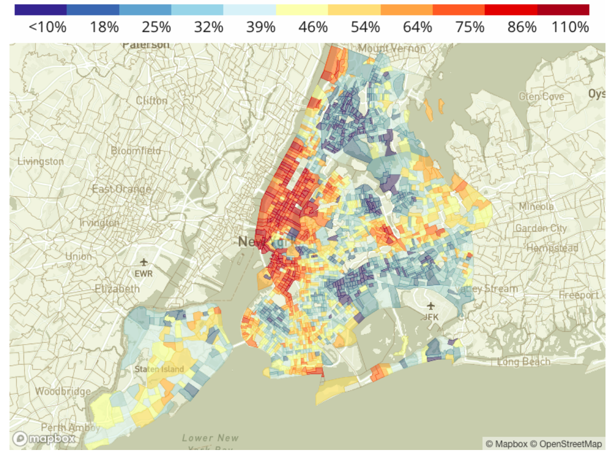

Figure 11. College Degree Attainment

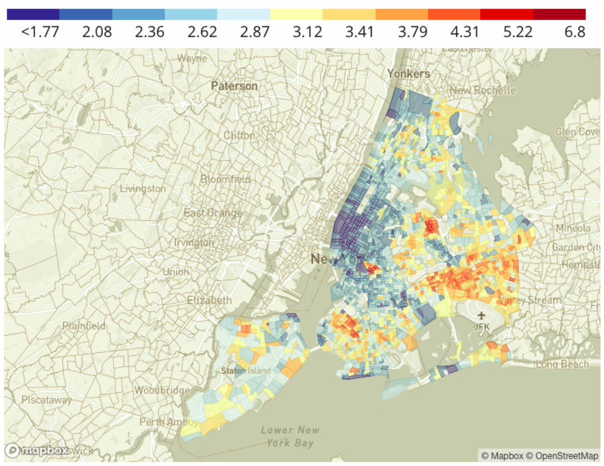

Figure 12. Household Size

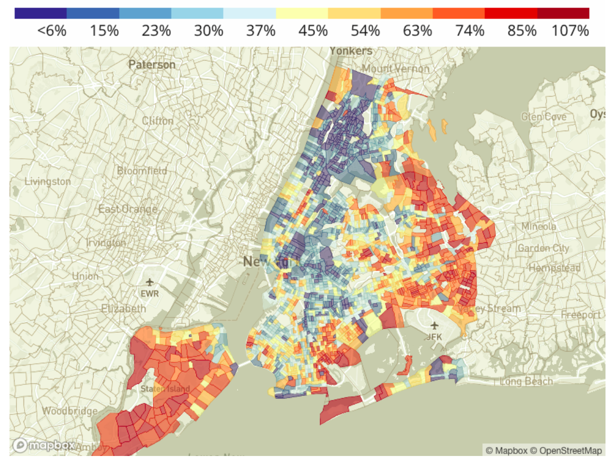

Figure 13. Home Ownership Rates

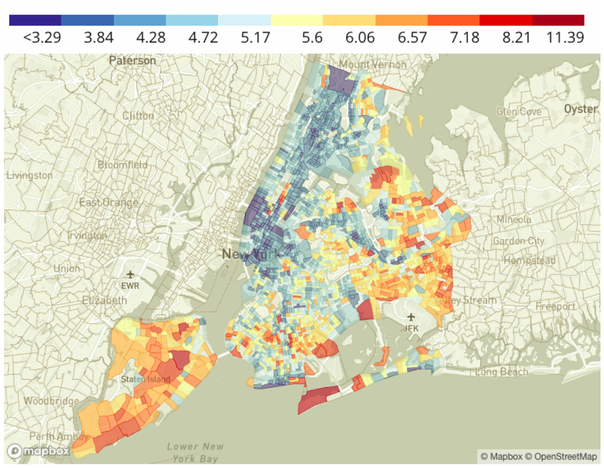

Figure 14. Rooms per household

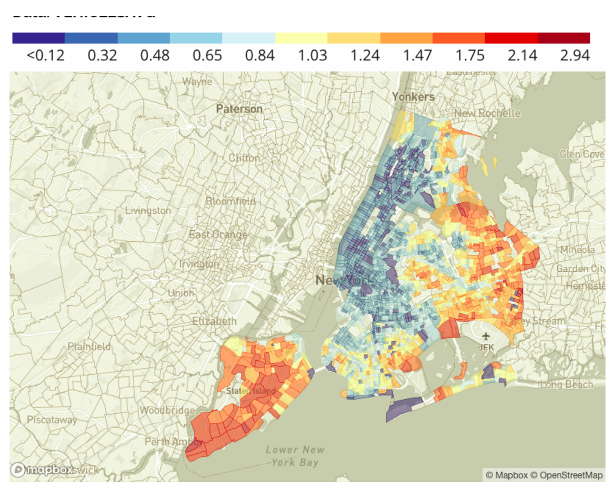

Figure 15. Vehicles per Household

3) Build a predictive model
Using the nationwide survey and selected household and geographic characteristics, we run a computer program that identifies how strongly each of those household characteristics correlates with the survey results. This technique is called multiple linear regression, and is a type of machine learning - the computer sees a lot of input data (the household and geographic characteristics) and learns how to predict what the outcome will be (the survey result). The computer then gives us an equation that takes each of those household and geographic characteristics and produces an estimated result.

A single linear regression might take this form:

$$y = mx + b$$

where y is the survey result (dependent variable), x is the household and geographic characteristics (independent variable), m is the computer's predicted correlation between x and y (slope), and b is a fixed value that adjusts for any underlying base discrepancy between x and y when x is equal to 0 (intercept).

In multiple linear regression, the equation takes on a more complex form:

$$y = m_1x_1 + m_2x_2 + m_3x_3 + \ldots + b$$

where in this case, each x (x_1, x_2, x_3, etc.) is a different household or geographic characteristic, with its own unique correlation (m_1, m_2, m_3, etc.) that together add up to make the overall result. The number of x variables depends on the sub-model and available data. All EcoDataLab sub-models use at least six variables (…x_6), with some using a dozen or more to get the most accurate prediction possible.

In addition, many of the values we are considering do not scale linearly. Instead, the models often look more like this:

$$\ln(y) = m_1x_1 + m_2{*}\ln(x_2) + m_3x_3 + \ldots + b$$

where the survey result might actually be scaled as a natural log (ln) variable, and some of the household and geographic characteristics are also calculated using its natural log (or sometimes both its ordinary and natural log values). This generally occurs in cases where there are nonlinear effects from household characteristics, and smaller values have different implications than larger values. For example, a household of 2 is typically two adults, whereas a household of 3 typically includes a child, which can significantly change consumption patterns. Similarly, consumption patterns based on income change significantly once basic needs are met and "luxury goods" start being consumed.

4) Run the model using local data
With these multiple linear regression models built (see above), we then collect over 200 points of local data - mostly census and climate data, from federal sources including the US Census Bureau, the National Oceanic and Atmospheric

Administration (NOAA), and also things like energy prices, inflation rates, fuel economy, and emission factors from sources including the Energy Information Agency (EIA), the Bureau of Labor Statistics (BLS), the Department of Energy, and the Environmental Protection Agency (EPA). Those values are transformed to fit the required inputs to the model, and then the model is run with that local data as the independent (x) variables in the model.

5) Make final adjustments to consumption estimates
While the multiple linear regression model helps us estimate consumption, the model doesn't perfectly resemble reality. We adjust for these discrepancies by comparing the model's predicted results with real-world data wherever available, and scaling the model outputs where real-world data isn't available.

To achieve this, we compare the model results with the actual results for the most granular level of data available. This can be national-level data (in the case of surveys), state-level data (in the case of transportation), or locality-level data (in the case of energy or water consumption). For cases where real-world data is available at the geographic scale of interest, we use the real-world data in place of the modeled data; otherwise, we run the model at a geographic level at which data is available and use that to create a scaling factor, which we use to correct the locally modeled data. For example, the standard approach to energy modeling is to compare modeled state-level energy use with real-world state-level energy data, and then use that scaling factor to adjust a city or county's modeled energy use.

6) Calculate emissions
After calculating consumption using the models, we then calculate emissions. Most consumption emissions are calculated using the US EPA's USEEIO Model,[3] which bridges the gap between consumption (dollars) and emissions ($MTCO_2e$). This model includes data on emissions by sector and supply chain stage, allowing us to differentiate between emissions associated with production, transport, wholesale, and retail for all US emissions. Emissions associated with fixed capital investments (e.g. buildings & infrastructure construction, excluding residential construction) are also incorporated across all sectors.

For electricity emissions, we use EPA's eGrid emission factors,[4] detailed at the zip code level and then scaled to any geography. For all other direct consumption of fuels (natural gas / methane, gasoline, etc.), we use the latest IPCC GWP values and best available academic literature to estimate life-cycle emissions. This includes fugitive and non-CO_2 GHG emissions, as well as any radiative forcing effects from other emissions (such as particulate matter or contrails).

When working with local jurisdictions, we replace these national or grid average emission factors with the best available local data. We contact state agencies to procure detailed vehicle registration data, which we combine with US DOE fuel economy data[5] to get the most granular and accurate estimate for fuel economy of

[3] https://www.epa.gov/land-research/us-environmentally-extended-input-output-useeio-models
[4] https://www.epa.gov/egrid
[5] https://fueleconomy.gov/

local residents' vehicles. We work with local jurisdictions to identify local utilities and their geographic coverage, and their local emission factors for electricity, water & wastewater, or methane leakage rates.

Model Input Variables

The consumption models use the following six variables: household size, average income, vehicle ownership, home ownership, share of household respondents with a bachelor's degree or higher (educational attainment), and number of rooms (home size).

The vehicle miles traveled model uses household size, average income, vehicle ownership, home ownership, and educational attainment, along with commute time to work, drive alone to work, number of homes per square mile, number of employed people per square mile, employed people per household, family status, children per household, youth per household, adults per household, and Census region.

The home energy models use household size, average income, home ownership, and home size as well as detached home status, heating and cooling degree days, statewide average price of electricity, statewide average price of natural gas, and census division.

Technical Details

U.S. Household Carbon Footprints, 2007 – 2019

Our methodology starts with detailed results from the Consumer Expenditures Survey (CE) for average U.S. households for the years 2007 to 2019, aggregated into a single file. The CE, conducted by the Bureau of Labor Statistics (BLS), is the only annual national survey of household consumption in the United States. There are a total of 95 categories and subcategories of expenditures for everything U.S. households consume, including a detailed breakdown of food, utilities, home construction, transportation, household goods and services. As a starting point for our analysis, we map CE expenditure categories to Personal Consumption Expenditures (PCE) developed by the Bureau of Economic Analysis (BEA). Each PCE maps to one or more sectors of the US economy, and each sector has associated full supply chain emissions available through the US EPA's USEEIO model. We use BEA's PCE Bridge Tables for 2012 to assign emissions to cradle-to-gate, transportation to market, and trade. We then create custom emission factors (grams CO_2e per dollar of CE expenditure) based on our detailed mapping of sectors, PCE and CE categories. This table converts average U.S. household expenditures to total U.S. emissions, broken down by each CE category and in total.

These custom emission factors are then increased to account for fixed capital investments (buildings and infrastructure). Emissions from fixed capital are attributed to each sector based upon that sector's economic weight. Because the USEEIO model is only available for the year 2012, we must extrapolate emissions to additional years. The steps to back-casting and forecasting are as follows: 1) adjust modeled and real-world household expenditures into 2012 U.S. dollars using the category-specific Consumer Price Index (CPI) for each category, which is also collected by the Bureau of Labor Statistics, 2) adjust 2012 USEEIO emission factors backwards and forward in time using an average decarbonization rate (assumed 1%), 3) apply USEEIO emission factors with emissions from buildings & infrastructure incorporated as mentioned above, 4) substitute household gasoline, electricity, natural gas, and other fuels usage from sector-specific models based on other government sources (Energy Information Administration and the Federal Highway Administration), and 5) apply direct and indirect (well-to-pump) emission factors for fossil fuels and electricity consumed directly by households. This methodology allows us to consistently track changes in the quantity of household consumption over time using BLS data and the impact of consumption on emissions using best-available sources.

As reported in the San Francisco CBEI from 1990 to 2015 (Jones 2020), this consumption-based approach accounts for essentially all GHG emissions in the US economy but allocated to households and government. The figure below (from Jones 2020) compares the traditional territorial-based US GHG inventory (US EPA) with the consumption-based GHG inventory. The CBEI correlates very closely to the traditional inventory (within 10%). We currently assume imports are produced with the same carbon intensity as domestic production; future work will likely include a proprietary multi-regional input output model (MRIO) (such as Eora or Exiobase3) to account for the carbon intensity of imports. MRIO models allow for more granular analysis of trade between geographic regions, including between US counties and with other countries.

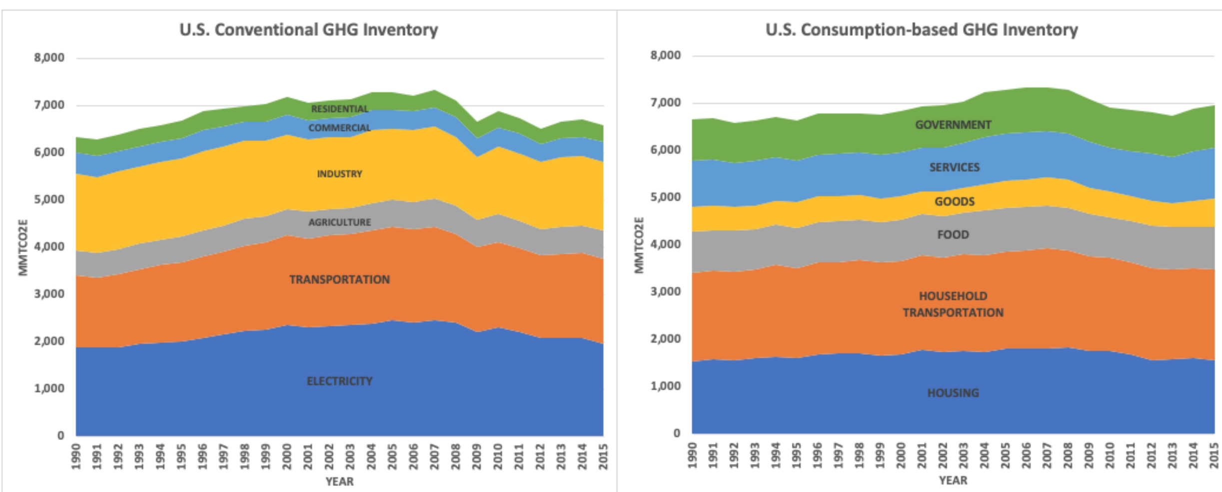

Figure 16. U.S. traditional (territorial) versus consumption-based GHG emission inventory

Transportation is the largest category of emissions in both the geographic and consumption-based approach. Emissions from residential (heating fuels) in the sectoral approach are combined with residential electricity, home construction, waste, water, and household operations in the consumption-based approach. Emissions from Industry in the sectoral approach are split into goods, services, transportation, housing and food. Emissions from Commercial in the sectoral approach only includes heating fuels, whereas Services in the consumption-based approach includes the full life cycle of goods and services consumed by the services sectors, as well as direct and indirect emissions from energy and transportation used by that sector.

Household Consumption
Our estimate of national U.S. household carbon footprints relies on accurate assessment of average household consumption in the Consumer Expenditures Survey. In the absence of survey data tracking actual household consumption for cities, we build econometric models that identify the primary driving factors of each category of consumption, and then apply model results to predict consumption based on variation in those same variables over time and space at local scales. After considerable experimentation with CE public-use microdata (Bureau of Labor Statistics 2019) we find six variables to have the most influence on consumption: 1) household size, 2) income, 3) home size, 4) home ownership, 5) education (college degree or higher) and 6) vehicle ownership.

The econometric models, while interesting and policy relevant themselves, also allow us to estimate consumption for every location across the United States. The American Community Survey (U.S. Census) provides estimates of each variable for every U.S. location down to block group scale. We can therefore estimate consumption for any and all U.S. locations (block groups, tracts, zip codes, cities, counties, states), based on national average consumption and how much each variable differs from national average values.

Modeled Electricity, Natural Gas and Fuel Oil Consumption
Annual residential electricity and natural gas consumption for New York City was provided by the Utility Energy Registry. Due to privacy considerations, energy consumption for Census tracts is rarely available for public disclosure. We therefore develop models of household energy use for each fuel (gas, electricity and fuel oil) by heating fuel type (for a total of 9 models) using household, geographic, and housing characteristics in the 2015 Residential Energy Consumption Survey (US Energy Information Administration 2015). The variables include average household income, percentage of homes that are single-family detached, home ownership rates, natural log of household size, natural log of rooms (home size), cooling degree days (base 65), heating degree days (base 65), state price of electricity, state price of natural gas, Census division. Our modeled estimates are used wherever NYC data is unavailable (such as for historical emissions or finer geographic resolution).

The modeled results are strongly correlated with actual results, at both the state and local level. The figure below compares modeled estimates of household electricity consumption (x-axis) for each US state with actual household consumption (y-axis). The goodness of fit R^2 is ~0.85, meaning the energy model explains about 85% of the variation in the data. Applying this model to each Census tract should produce reasonable estimates of household electricity consumption.

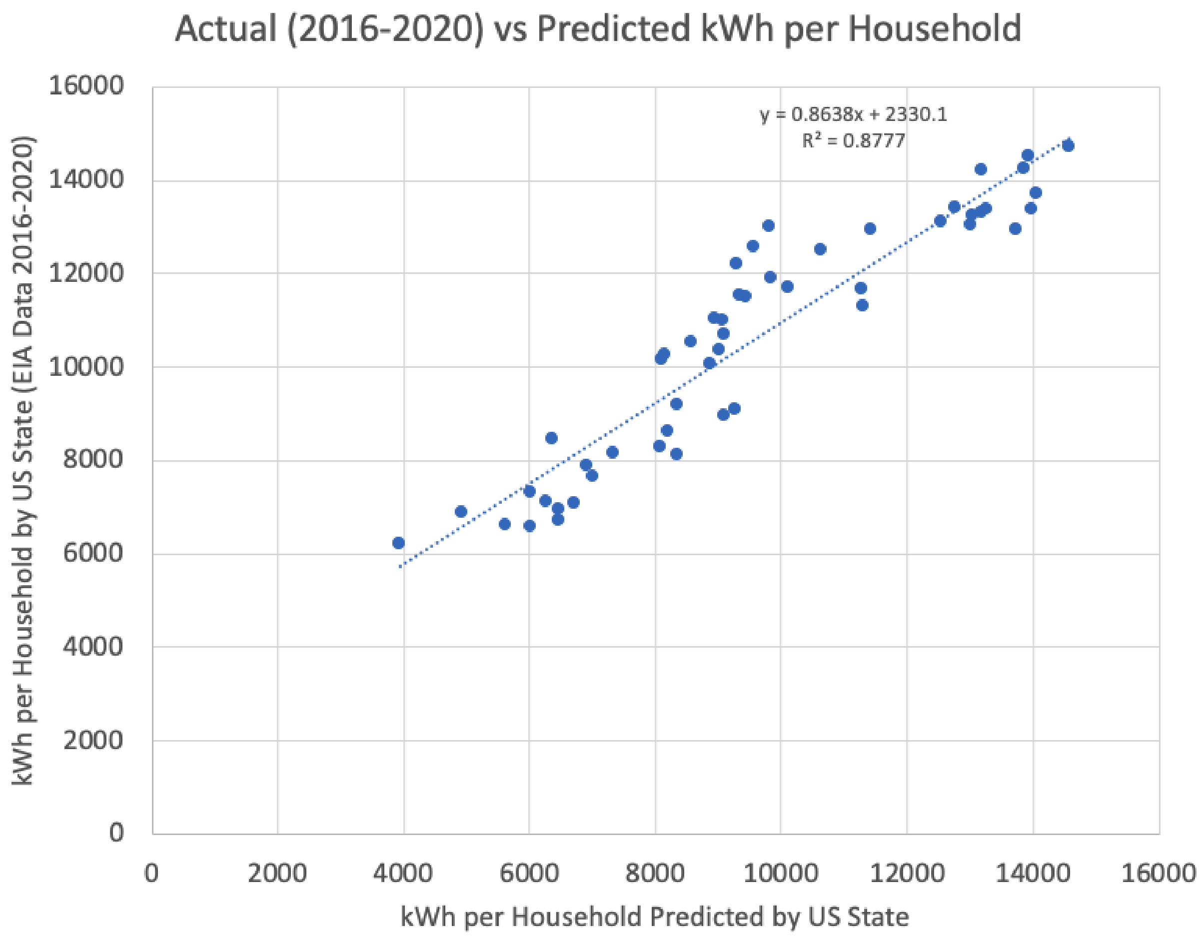

Figure 17. kWh Electricity per Household - Actual vs Predicted by US state

Validation of the natural gas models is shown in the figure below for U.S. states. The left-hand figure compares modeled natural gas per household for all homes that heat with gas (x-axis) vs. actual natural gas consumption per residential gas customer. The estimate is stronger when combining all heating fuel types, including those who have no gas (R^2 is ~0.93), shown in the right-hand figure.

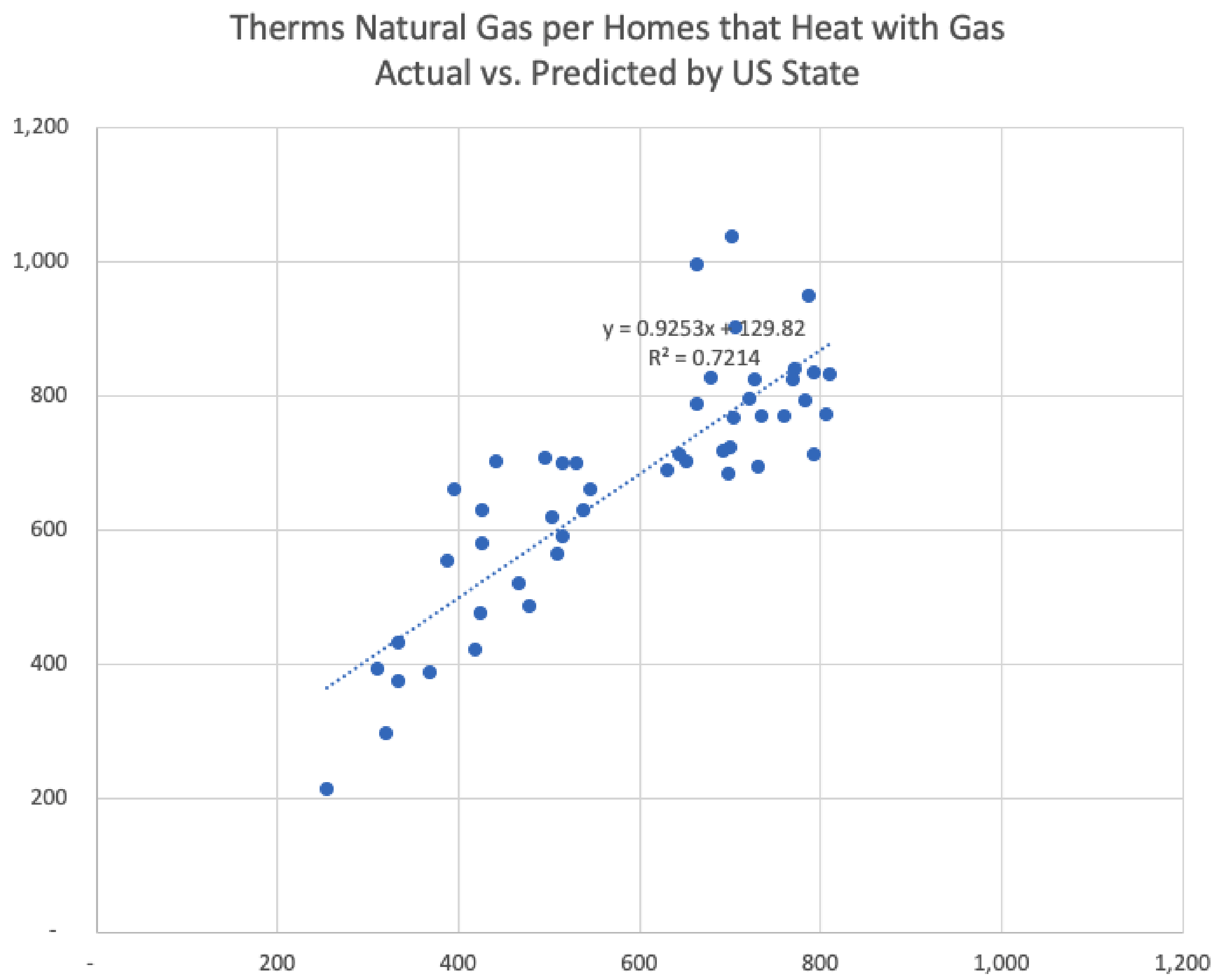

Figure 18. Therms Natural Gas per Home - Actual vs Predicted by US state

Weather, demographics, home characteristics and energy prices are sufficient to predict average energy consumption of thousands of households. At smaller scales, such as Census tracts (and particularly low-population tracts in New York City), we can expect cases where the fit is not as strong.

The model also does not include local policy, including building codes and variations in building stock, which could further limit our ability to accurately predict household energy consumption. Individual behavior also plays a role. Communities with high levels of awareness and concern for energy efficiency and conservation may have lower estimates than predicted. These differences tend to average out with larger numbers of households.

Fuel oil is somewhat more difficult to predict since a smaller number of homes use this fuel nationally. We use weather (heating degree days), average household income and home structure (percentage single-family detached) to predict fuel oil consumption for each primary heating type. We have not identified a reliable external source of fuel oil consumption data to validate our models.

Modeled Motor Vehicle Miles

Motor vehicle miles traveled (VMT) are modeled from micro data respondents in the National Household Travel Survey (Oak Ridge National Laboratory 2013). Model variables are: number of vehicles per household, home ownership, household size, average household income, number of workers, workers per square mile, housing per square mile, educational attainment, time commuters travel to work, percentage of commuters who drive alone, children per household, youths per household, adults per household, log of household size and log of income. This is the latest and most robust travel demand model we could construct using the NHTS data.

Air Travel

Economic expenditures on air travel are approximated using the Consumer Expenditures Survey (CEX) (Bureau of Labor Statistics 2013) with household income as the only independent variable (i.e. the other variables used throughout the other CBEI models are not used for air travel estimates - only income). Household income is the largest factor contributing to air travel in the United States, with other variables, such as population density, trip distance and the presence of low-cost airlines having mixed and often complex relationships (Bhadra 2003).

Regression analysis on the portion of public transit spending in the CEX provides a coefficient for income that allows for an estimate of consumer spending on air travel.

The US Department of Transportation's Domestic Airline Consumer Airfare Report, Table 5 provides passenger miles and fares for the top 1,000 contiguous US city-to-city markets. In 2019 the average cost per passenger mile was 19.1 cents.

Year	Passenger Miles	Passenger Fares	USD per PM
2010	3,450,934,771	597,902,100	0.173
2015	3,961,672,575	773,965,481	0.195
2016	4,149,605,147	768,752,794	0.185
2017	4,308,004,016	793,232,515	0.184
2018	4,502,083,367	844,030,476	0.187
2019	4,605,258,037	881,878,038	0.191
2020	1,681,150,343	273,945,724	0.163
2021	2,179,951,106	347,154,638	0.159
Grand Total	**43,145,573,678**	**8,082,064,588**	**0.187**

Table 5. Passenger miles and fares for the top 1,000 contiguous US city-to-city markets

Emission factors for air travel were calculated using total passenger miles traveled and associated air travel emissions in the US to get an estimated average grams per passenger mile, which combined with the cost per passenger mile allows for the generation of an air travel emissions factor estimated in grams per dollar.

This emission factor is then increased to account for life-cycle effects of production of aviation fuels, as well as the effects of high-altitude radiative forcing.

While there is considerable variation in both direct and indirect emission for individual flights, these differences should be moderated when considering average values for multiple flights by multiple households in each location.

Limitations

Unlike other CBEI approaches, this model approach allows for some ability to see the effect of policy and to track changes over time. The current approach offers this improved tracking by including more policy-relevant variables, including home size, household size, home ownership, education, income, population density and vehicle ownership. The study also includes local data on energy consumption, carbon intensity of electricity, water, and waste.

However, local changes in policy, behavior, infrastructure and most technology that might affect consumption or emissions in ways beyond the model variables are not included in the current approach. If a local policy changed consumption patterns or the carbon intensity of products or services consumed, we would not be able to monitor this with the current methodology. Additional data could supplement the approach in future studies.

The current study does not include an estimate of total study error. Ideally, each estimate of consumption and emissions would include uncertainty bounds and analysis of error. Potential sources of error include reporting error in household survey day, sampling error, model error, categorization error and other errors typically associated with input-output models (in this case, the USEEIO). These errors are known and could be propagated through formulas in future research.

We also assume the carbon intensity of imported goods to be the same as domestically produced goods, and are not able to track the countries of origin of emissions associated with local consumption with the current model. This assumption may affect individual products, such as computers, but is unlikely to have a large impact overall since the United States has a large, fairly carbon-intensive production system, with considerable electricity production from coal, similar to many importing countries. Future studies could incorporate a proprietary multi-regional input-output model to provide better data on the effect of international supply chains and locations consumption-based emissions.

We assume that price corresponds with “value added” economic activity. If New York residents, on average, purchase higher priced goods, then the methodology will linearly scale emissions up with prices. This scaling is appropriate if higher prices are the result of additional economic activity, such as importing products from abroad, but is problematic when prices are artificially raised, such as for branding purposes alone. Conversely, cheaper products will result in lower emissions in the model. Generally, we assume that price differences average out over thousands of households.

Appendix 2: US Emissions by Supply Chain Stage

Consumption-based emissions occur at many points in the supply chain. Emissions are generated in production, during transport (by rail, sea, road, or air), in wholesale and retail, and use. In some cases, disposal also generates emissions; however, post-consumer use, which would include recycling or disposal, also sometimes results in storing carbon that would otherwise be re-emitted. This model does not include emissions from post-consumer use.

Household Emissions by Supply Chain Stage - US Average

Figure 20 below shows the share of emissions associated with production, transport, sale, and use for each category of goods. (Because post-consumer use emissions are sometimes negative, they are not included on this chart).

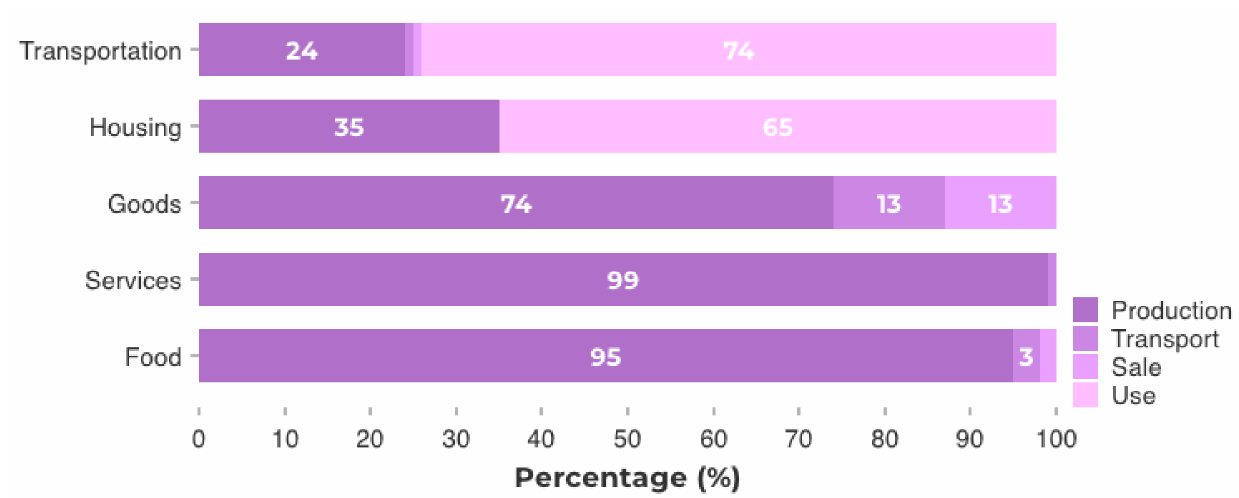

Figure 19. Household Emissions by Supply Chain Stage - US Average

Overall, emissions from transportation and housing are dominated by "use phase" emissions - the burning of fossil fuels (such as gasoline or the methane in natural gas) for transportation or home heating energy. This "use phase" - primarily gasoline combustion - makes up nearly 74% of household transportation emissions. For housing emissions, "use phase" emissions (electricity and home heating fuels) make up 65%.

For food, goods, and services, however, use-phase emissions are practically zero. These categories have some transport and sale emissions, but are overwhelmingly dominated by production emissions.

Pre-Consumer emissions breakdown - US Average

The chart below shows the pre-consumer (production, transport, and sale) breakdown of emissions by category.

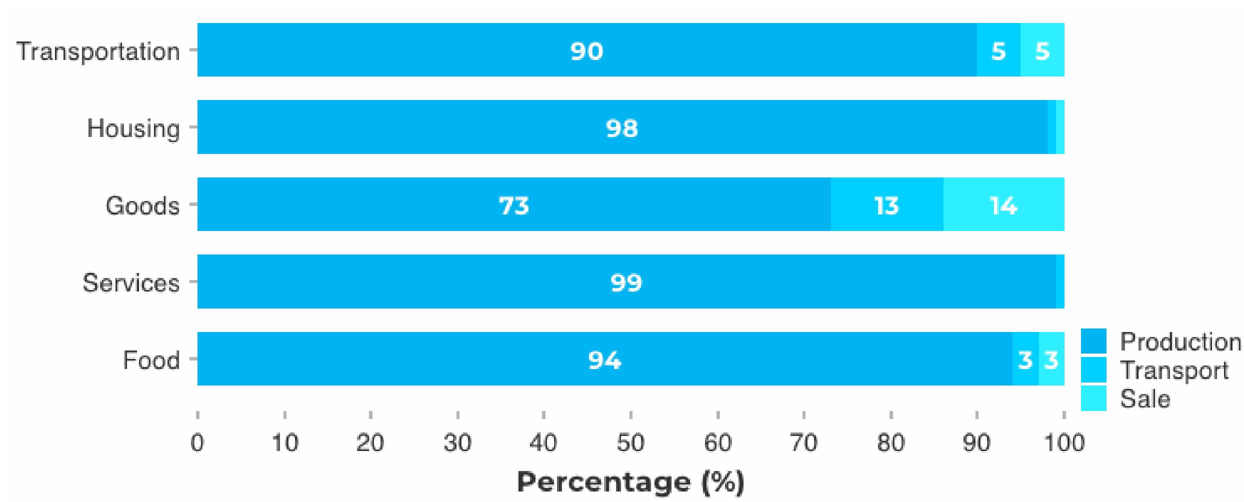

Figure 20. Pre-Consumer Emissions Breakdown - US Average

Pre-consumer emissions associated with Private Transportation (that is, prior to a consumer using a vehicle) are predominantly from production (90%). Roughly 50% of these emissions are associated with the production of fuel (oil extraction & refining); the remaining 50% are from the production of vehicles and vehicle parts. Most of the transport emissions in this section derive from the transport of used vehicles, while sales emissions mostly derive from the sale of transportation fuels (ie. gasoline).

For Housing, over 99% of pre-consumer emissions occur in production. This is dominated by the production of natural gas and the construction of homes, apartments, and other lodging (including hotels). The small portion of these emissions attributable to transport and sale are entirely due to the transport and sale of fossil fuels (and wood) used for home heating.

For Goods, only about 74% of emissions come from production. About 13% of emissions from goods comes from transportation, and 14% comes from retail. The "Transport" category includes truck, train, air, and sea travel; truck travel emissions account for more than 90% of the emissions associated with the transport of goods. If it were its own category, truck travel would make up 12% of goods total emissions, and all other transport would be just 1%. Similarly, the “Sale” category includes both wholesale and retail sale of goods. Retail makes up over 90% of sale-phase emissions, and if it were its own category would account for 13% of total emissions associated with goods (with wholesale comprising <1%).

Like Housing, pre-consumer emissions from Services are overwhelmingly (99%+) from production. The Services category is primarily made up of activities like healthcare, education, entertainment, and financial services; most involve little to no retail or transportation to provide, so emissions associated with these services occur in the construction and operation of buildings, business travel, procurement, etc.

Lastly, for Food, roughly 95% of emissions occur in production. Food emissions primarily come from application of nitrogen fertilizers and enteric fermentation (methane released from digestion by cows and other livestock). These emissions significantly outweigh the emissions associated with transportation or sale of food.

Appendix 3: CBEI and CEX Categories and Sub-Categories

The table below shows the relationships between the listed CBEI categories, sub-categories, and corresponding Consumer Expenditure Survey categories from the Bureau of Labor Statistics:

Category	Sub-Category	Corresponding CEX Sub-Category(s)
Transportation		
	Gasoline*	Gasoline and Motor Oil
	Vehicle Purchases	Vehicle Purchases (net outlay)
	Other Vehicle Expenses	Other vehicle expenses
	Air Travel	Public and other transportation
Housing		
	Shelter	Shelter, less Other Lodging
	Natural Gas*	Natural gas
	Electricity*	Electricity
	Other Lodging	Other Lodging
	Other Heating Fuels*	Fuel oil and other fuels
Food		
	Eating Out	Food away from home
	Meats, Poultry, Fish, & Eggs	Meats, poultry, fish, and eggs
	Other Food	Other food at home
	Dairy	Dairy products
	Alcoholic Beverages	Alcoholic beverages
	Fruits & Vegetables	Fruits and vegetables
	Cereals & Bakery Products	Cereals and bakery products
Goods		
	Furnishings & Appliances	Household furnishings and equipment

Apparel	Apparel and services
Housekeeping Supplies	Housekeeping supplies
Personal Care Products	Personal care products and services
Entertainment Goods	Audio and visual equipment and services
Misc Goods	Reading, Tobacco smoking supplies
Services	
Healthcare	Healthcare
Entertainment Services	Fees and admissions
Education	Education
Misc Services	Miscellaneous, Personal Care Services, Household Operations, Cash contributions
Insurance & Pensions	Personal insurance and pensions

*Not calculated using a CEX-derived model. Either uses real-world data or more complex modeled estimates (e.g. from NHTS or RECS).

Appendix 4. Other Consumption-based Emissions

Government

In this CBEI, government agencies are considered final demand the same way households are, and government emissions are not attributed directly to households. These emissions are not insignificant – based on GDP data and the same USEEIO emission factors discussed in Appendix A, federal, state, and local governments across the US had emissions totaling over 660 million $MTCO_2e$. Of this total, roughly 69% came from state & local governments, with the remaining 31% from the federal government split between defense (24%) and non-defense sectors (7%).

Like households, government emissions include transportation, buildings, food, and procurement of goods & services. Transportation emissions include the use of government vehicles, aircraft, trains and buses, police and firefighting vehicles, ambulances, and more (because public transit is heavily subsidized in the US and associated emissions are not directly related to consumer spending, these emissions are allocated to the government category in this methodology).

Government emissions from buildings include natural gas used for heating and water heating, as well as electricity use associated with the operation of the building. Government buildings include agency or department offices, legislatures, public colleges and universities, local schools, ports and airports, courts and prisons, post offices, military bases, some museums, research laboratories, libraries, water treatment plants, some hospitals, and more.

Embodied emissions from construction, including infrastructure, are also included. Roads, highways, and bridges all have large emissions associated with their construction. Governments also build and maintain local water supplies and resources, as well as some railway and public transit infrastructure, with additional emissions associated. Lastly, other purchases of food, goods and supplies, and services all have emissions associated with them as well.

Government consumption, and associated emissions, are not linked to particular household characteristics or activities in readily traceable ways. While some government activities can be linked to certain households (such as direct cash transfers for unemployment insurance or social security; and healthcare coverage through Medicare, Medicaid, or veteran's benefits) other government activities, like infrastructure construction and maintenance, national defense and public safety (police & fire), R&D spending, and parks maintenance cannot be attributed directly to households based on any discernible characteristics.

As a result, these emissions can only be effectively allocated to households on a flat average basis. If these emissions were allocated to households, it would be an average of 5.5 $MTCO_2e$ per household. For New York City, this would work out to an additional 17.66 million $MTCO_2e$ citywide. These "hidden" emissions are not otherwise captured in the CBEI, but still contribute to overall emissions nationally and globally.

Capital

Emissions from construction of non-residential buildings and infrastructure are considered "fixed capital" emissions. These emissions are incorporated into the emission factors for all goods and services. This CBEI considers emissions from construction that may occur anywhere in the world. As a result, even a jurisdiction that halted all construction and infrastructure maintenance would still have consumption-based emissions associated with construction occurring elsewhere in the world. A separate type of analysis could be conducted to specifically review local data on building construction and estimate scope 3 emissions associated with that activity. This would not be a household consumption-based approach because such an analysis would evaluate all emissions associated with construction, not just the share of emissions attributable to local residents' use of the infrastructure or facility.

Appendix 5: NYC Tract-level Maps

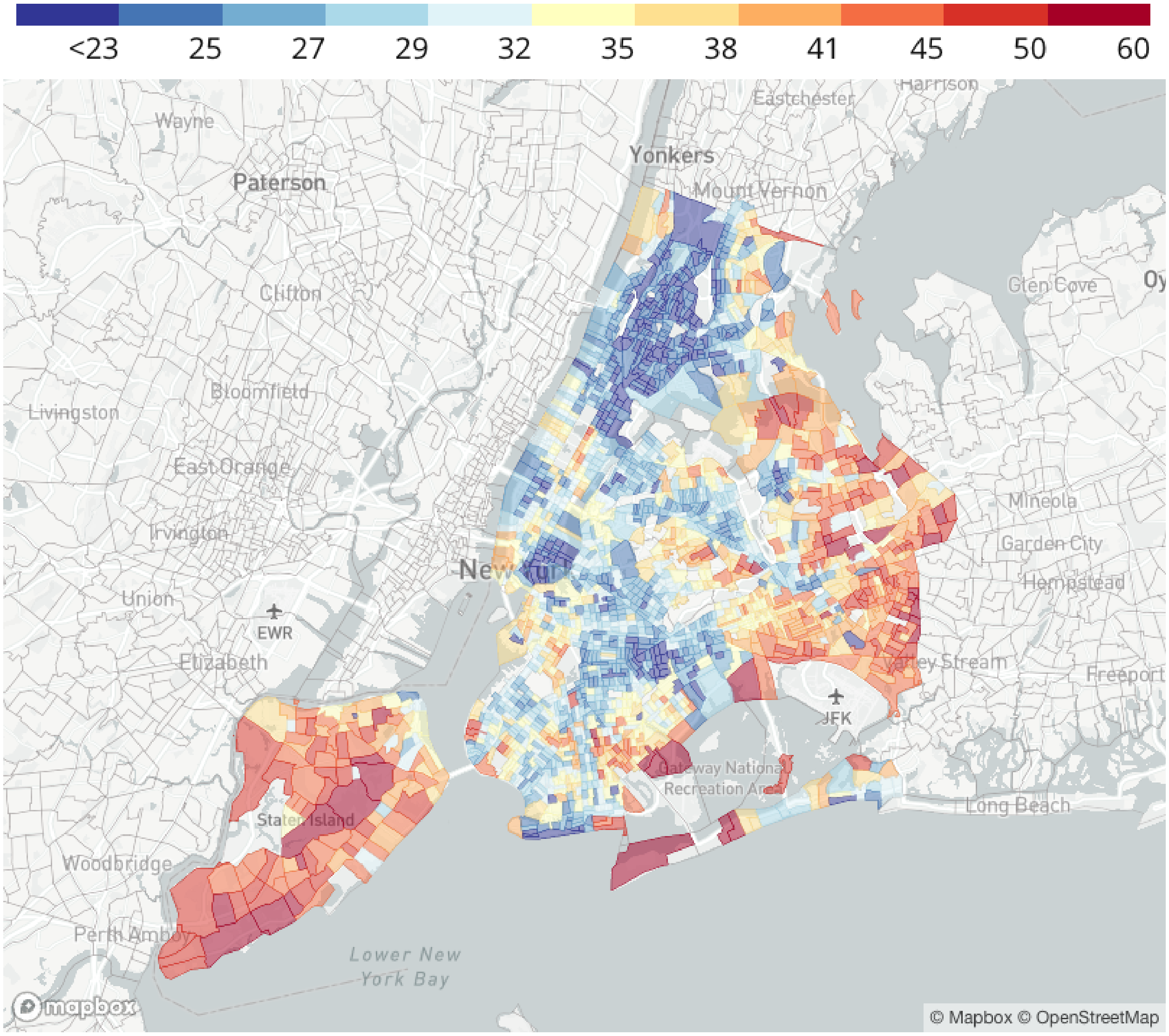

Figure 22. Consumption-Based Emissions Map (MTCO$_2$e per household)
Source: https://www.ecodatalab.com/cbei/ny/nyc/map/TotalEmissions

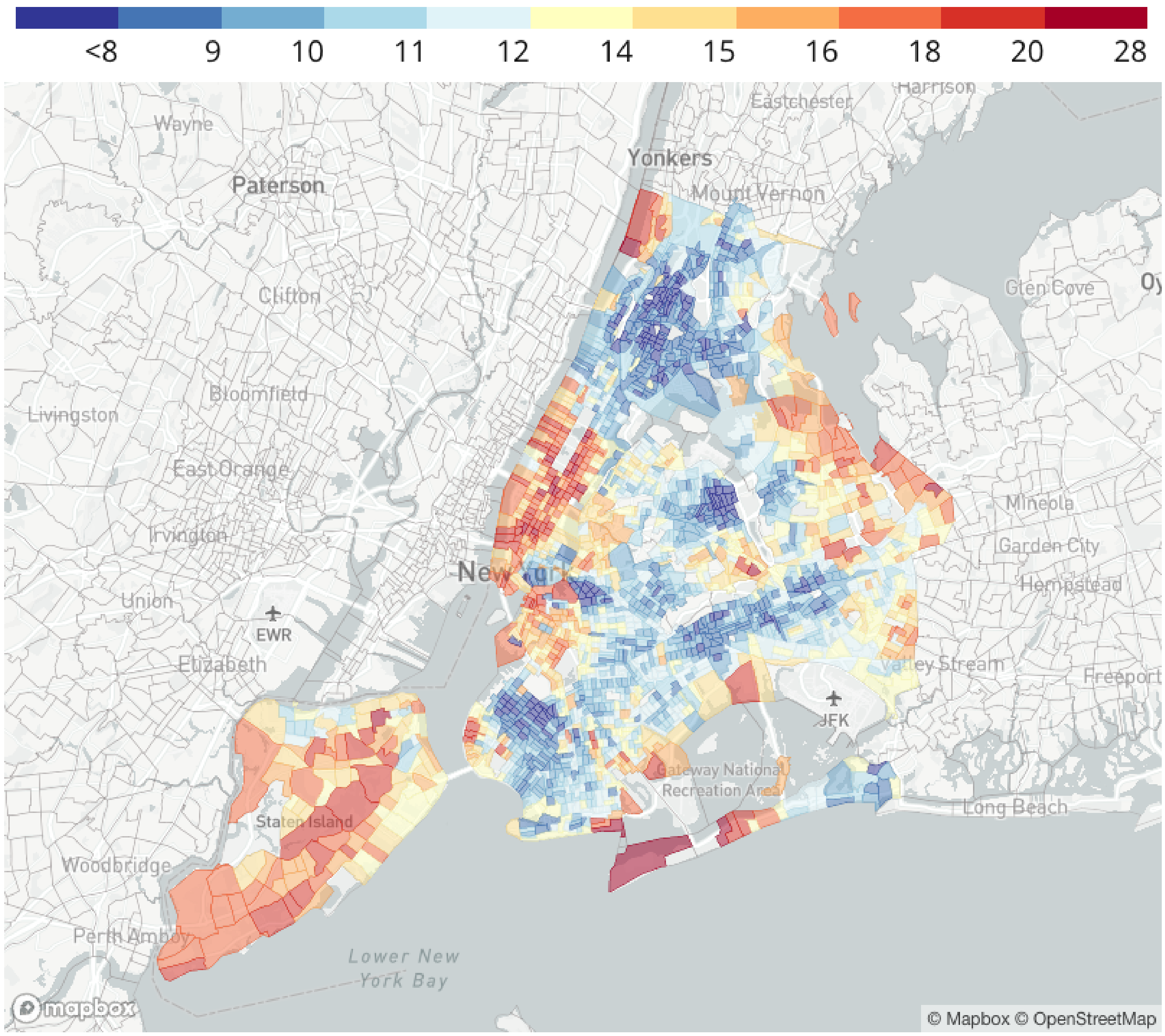

Figure 23. Consumption-Based Emissions Map ($MTCO_2e$ per person)
Source: https://www.ecodatalab.com/cbei/ny/nyc/map/TotalPerCapitaEmissions