Appendix A:
Methods and Data

Pathways to Deep Decarbonization in New York State

For the New York State Energy Research and Development Authority

June 24, 2020

Energy+Environmental Economics

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1 Introduction and analysis overview

New York State Energy Research and Development Authority (NYSERDA) commissioned Energy and Environmental Economics, Inc. (E3) to investigate a potential transformation of New York State's energy economy to one which achieves carbon neutrality by 2050, a goal set by the Community Leadership and Climate Protection Act (CLCPA).[1] The CLCPA also includes specific targets to decarbonize the State's electricity sector, such as:

+ 6 gigawatts (GW) of distributed solar by 2025
+ 70% renewable electricity by 2030
+ 9 GW offshore wind (OSW) by 2035
+ 100% zero-emissions electricity by 2040

The study evaluates the feasibility and timing of achieving the State's greenhouse gas (GHG) emissions reduction goals of 40% by 2030 and 85% by 2050 from 1990 levels in a manner consistent with achieving carbon neutrality by 2050.

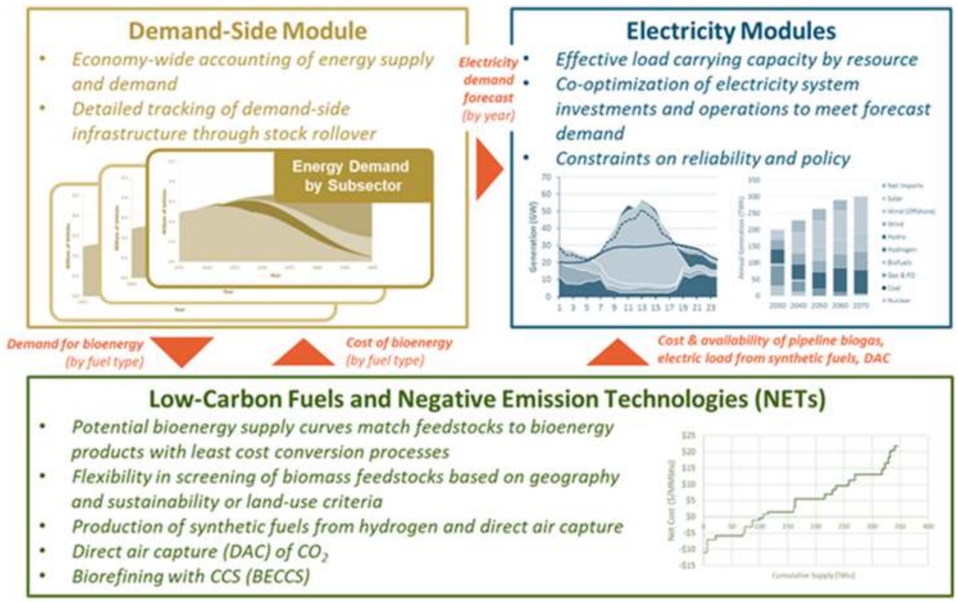
The CLCPA requires additional reporting of emissions associated with "extraction and transmission of fossil fuels imported into the state," as well as the adoption of a 20-year global warming potential, a metric that emphasizes the near-term climate impacts of short-lived climate pollutants such as methane. The calculation of a 1990 baseline that includes these new requirements is currently underway. This analysis uses available 1990 data from prior inventory reports and adopts the GHG accounting framework from those prior reports.[2] Future decarbonization pathways analysis will align statewide GHG emissions accounting with these CLCPA provisions and updated baseline.

Although this analysis captures economy-wide GHG emissions and mitigation opportunities, its analytic focus is on the electricity, transportation, buildings, and industrial sectors. In addition to future refinements in these sectors, additional analytic work will be needed to improve characterization of non-combustion sources and associated mitigation opportunities.

The study addresses New York's energy economy on an annual time scale, with key outputs including annual energy demand and emissions by fuel; stocks and sales of energy-consuming devices; and electricity supply infrastructure including both generation and transmission upgrades. Inputs to the models used in this study include sale shares of new devices (e.g., vehicles, building energy and efficiency systems), cost and performance characteristics of infrastructure (both supply- and demand-side), and projections of fuel prices.

To perform this analysis, E3 analyzed two key processes: the evolution of energy demand and the evolution of energy supply. E3 used a variety of tools in this analysis effort. A diagram of this multi-model framework is presented in Figure 1.

Figure 1. Economy-wide energy model linked to low-carbon fuels and electricity models



This analysis used a suite of tools to characterize the evolution of New York energy infrastructure and emissions. The demand-side module calculated direct[i] energy use and associated GHG emissions, as well as non-combustion related emissions and sequestration. The demand-side module interacted with the low-carbon fuels and negative emissions technologies models, as well as the electricity modules. The electricity modules took electricity demand, projected by the demand-side module, and co-optimized investment and operations of the electric power system to meet electric load reliably while complying with applicable electric sector GHG emissions and renewable energy targets. The low-carbon fuels module calculated availability of low-carbon fuels, which were used within the demand-side module as an option to reduce emissions from

[i] Emissions from direct fuel use are emissions associated with fossil fuel combustion when fossil fuels provide energy service. For example, combusting natural gas to provide heat or combusting gasoline in an engine are examples of fossil fuel combustion which result in direct fuel use emissions. Indirect energy related emissions are emissions produced even when the fuel used at the device is GHG free. For example, electricity and hydrogen both emit no GHG emissions when used in buildings, industry, or transportation; nevertheless, the production of electricity or hydrogen creates emissions and this report considers these indirect energy related emissions.

fossil fuel combustion by substituting fossil fuel combustion with low-carbon fuel combustion.

The core analytical tool in analyzing energy demand was the New York PATHWAYS model. E3 developed the New York PATHWAYS model using the Long-range Energy Alternatives Planning (LEAP) software tool,[3] an application that tracks energy consumption and GHG emissions sources and sinks throughout the economy in user-defined scenarios. The New York PATHWAYS model outputs energy use and GHG emissions in all sectors of the economy except for emissions produced by electric generating units; these were represented in the RESOLVE electricity sector model and are described in more detail in Section 8. A key feature of PATHWAYS is its ability to characterize stock rollover in major equipment categories (energy uses in buildings and transportation fleets). By accounting for appliance and vehicle lifetimes, the stock rollover feature of PATHWAYS assists users in analyzing the rate of change necessary to achieve decarbonization goals and captures potential path dependencies. For example, increasing sales of natural gas heaters and reducing sales of fuel oil heaters in the 2020s time frame might help the State achieve 2030 GHG emissions goals, but without significant blending of low-carbon renewable natural gas into the natural gas distribution pipeline or further fuel switching some natural gas heating to electric heating, this strategy would not be enough to achieve the State's 2050 emissions targets. The stock rollover feature in PATHWAYS allows a user to track these kinds of dynamics.

E3 built a model of New York State's energy and non-energy emissions sources and projected energy demand and economy-wide emissions from 2015 through 2050, using different scenarios to understand trajectories and pathways which can be used to achieve carbon neutrality of the state's emissions. This report uses the term PATHWAYS to refer to the representation of New York energy system which E3 built. In this study PATHWAYS includes direct energy use, emissions associated with direct energy use, and non-combustion related emissions and sequestration. The emissions associated with electricity generation are tracked within the RESOLVE model, which is described in further detail in Section 8.

To characterize demand-side infrastructure in this study, E3 used two approaches: a "stock rollover" approach where sufficient data were available, and a "total energy" approach when sufficient data were not available. In the stock rollover approach, E3 characterized infrastructure stock, and energy and emissions associated with energy consumed by infrastructure, as new devices were added and old infrastructure was retired in each simulated year. In the total energy approach, E3 directly specified energy consumption in each simulated year based on scenario-specific inputs characterizing the amount of energy efficiency, potential for electrification, and potential for switching fossil fuel combustion to low-carbon fuel combustion. A more comprehensive description of stock rollover is provided in Section 2.3.1, while a description of the "total energy" approach is provided in Section 2.3.2.

As discussed in more detail in Section 3, Buildings; Section 4, Transportation; and Section 5, Industry a variety of measures that reduce greenhouse gas emissions were evaluated. These measures include but are not limited to energy efficiency, electrification, and substitution of fossil fuels with low-carbon fuels. For details on the mitigation options in each sector, please see the appropriate sections of this document.

The scenarios assessed included one counterfactual "Reference" scenario which includes adopted goals as of May 2019. These include but are not limited to the *Clean Energy Standard,*[4] energy efficiency targets consistent with *New Efficiency: New York* white paper,[5,6] emissions standards in New York's low emission vehicle program incorporating California GHG standards (i.e., the "ZEV mandate"),[7] and the New York City *Local Law 97 of 2019.*[8] In addition to this Reference scenario, E3 assessed a variety of "Decarbonization Pathways" scenarios which use distinct technology strategies and are designed to achieve the State's goals mandated by the CLCPA: 40% GHG emissions reductions by 2030, 85%

reductions by 2050, and net zero GHG emissions by 2050. Unlike general equilibrium models, where relative prices of infrastructure or energy dictate measure selection, in PATHWAYS, measure selection is constrained by other variables including but not limited to expert judgment, resource availability, and physical feasibility.[9]

One way to reduce GHG emissions from fuel combustion is to use low-carbon, or no-carbon, fuels such as advanced biofuels. To calculate the availability of advanced biofuels as a measure to reduce emissions from fuel combustion in certain end uses, E3 integrated a biofuel supply module that matched available biomass resources with least-cost biofuel conversion processes to provide biofuels to both energy demand and electric supply. The methodology for calculating the availability of biofuels is detailed within Section 6, Low-carbon fuels.

Annual electricity loads from the PATHWAYS model framework, as well as simulated hourly load shapes by end use, were used as inputs to the electric sector analysis. For details on the hourly load shaping methodology, which takes into account changing system dynamics of increased electrified space heating and vehicle electrification, see Section 7, Load shaping.

The electric sector analysis was performed using E3's capacity expansion and resource adequacy models, RESOLVE and RECAP. RESOLVE is an electricity-sector resource investment model that optimizes long-term generation and transmission investments subject to reliability, technical, and policy constraints. RECAP is a resource adequacy model that performs loss-of-load probability simulations to determine the reliability of resource portfolios. RECAP analysis was used in this work to determine the effective load-carrying capability (ELCC) of wind, solar, and battery storage resources. With load projections from PATHWAYS and ELCC curves from RECAP serving as inputs, RESOLVE was used to develop least-cost electricity generation portfolios that achieved New York's policy goals while maintaining electric system reliability. For more details on the electric sector analysis, see Section 8, Electricity generation.

Together, the models tracked the change in composition of the New York energy economy annually. This document highlights the methods and data surrounding this analysis effort.

2 Cross-cutting issues

2.1 Scope and segmentation

E3 followed the New York State GHG inventory[2] accounting framework to define the GHG emissions which the state is responsible for reducing. The GHG inventory identifies emissions associated with sectors and sources in a manner broadly consistent with Intergovernmental Panel on Climate Change (IPCC) guidelines.[2] In brief, this includes emissions associated with energy use in buildings, transportation, and industry; electricity generating units within the state; emissions associated with net imports of electricity; non-combustion emissions associated with industrial processes, agriculture, waste; and non-fuel energy emissions associated with oil and gas systems and incineration of waste. Different greenhouse gases have different climate impacts across various timescales, so the inventory uses a 100-year global warming potential in calculating carbon dioxide equivalent emissions.[ii]

The CLCPA requires additional reporting of emissions associated with "extraction and transmission of fossil fuels imported into the state," as well as the adoption of a 20-year global warming potential to measure the impacts of short-lived climate pollutants[iii] such as methane.[1] The calculation of a 1990 baseline that includes these new requirements is

[ii] Global warming potential is a measure of how much energy a GHG will absorb over a given period, relative to carbon dioxide; by definition carbon dioxide has a global warming potential of one. The United States primarily uses the 100-year global warming potential to measure the relative impact of different GHGs.

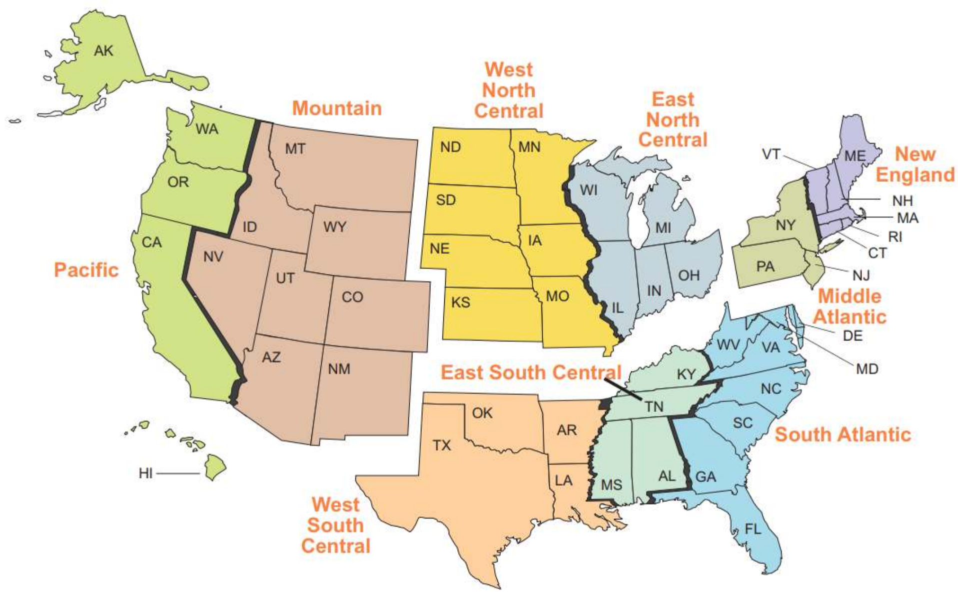
[iii] Short lived climate pollutants are GHGs with high global warming potentials but much shorter lifetimes than carbon dioxide. Main short lived climate pollutants are black carbon, methane, ozone, and fluorinated gases such as hydrofluorocarbons, which are ozone depleting substance substitutes.

currently underway. Future decarbonization pathways analysis will align statewide GHG emissions accounting with these CLCPA provisions.

With some energy demand, boundary conditions for energy usage attributed to a state need to be defined. For example, aviation and heavy-duty trucking involve energy usage across state lines, so a state can define its fuel responsibility as all fuel sold within state boundaries, or only the fuel sold to satisfy services demanded by the state's local population. E3 defined energy boundary by following the boundary conditions as described in the GHG emissions inventory. On the electricity supply side, it is impossible to analyze electricity consumption in New York State without accounting for electricity trade and links with neighboring zones. Thus, E3 included characterization of the electric systems within zones New York trades with, which include territories coordinated by Quebec, Ontario, and the regional transmission organizations PJM Interconnection LLC (PJM), and Independent System Operator New England (ISO-NE). These zones were simulated in significantly less detail than New York, but as New York is not an islanded grid it is impractical to characterize the state of New York without representing its electrical linkages to other regions as well.

To characterize energy demand in most devices, E3 primarily relied on data obtained from the input files and documentation to the EIA National Energy Modeling System (NEMS), including energy service demand by device type and census region[10] (New York is in the Mid-Atlantic region, as seen in Figure 2), and device-specific efficiency projections through 2040. In sectors where state-level data exists in addition to federal data, E3 substituted or combined data sets for a more complete representation of the sector. Note that in the first simulated year (2015), E3 benchmarked energy demand to various sources, including statewide GHG emissions data from NYSERDA and the New York State Department of Environmental Conservation (NYSDEC),[2] energy demand data segmented by sector and fuel from NYSERDA,[11] electric load data from the New York Independent System Operator (NYISO), [12] and vehicle mileage data from New York State Department of Transportation (NYSDOT) used by NYSDEC in analyzing mobile-source emissions for state air quality planning.[13]

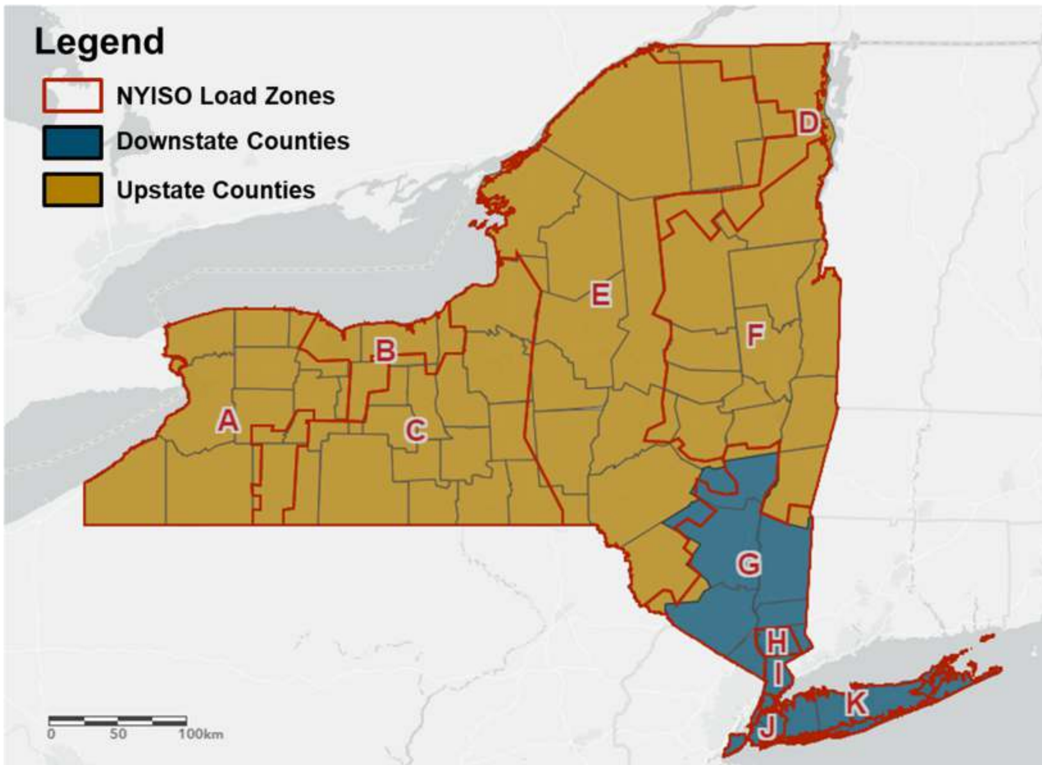
Figure 2. United States census divisions



Source: EIA NEMS[14]

E3 apportioned population, housing units, and commercial building square footage by county into upstate and downstate regions, defining the upstate region as counties within the NYISO zones A-F and the downstate region as counties within the NYISO zones G-J. The NYISO zonal borders do not map exactly onto county borders, so E3 allocated counties which lie in both upstate and downstate NYISO load zones into either the upstate or downstate region; see Table 1 for the county level geographic allocation E3 used in this study and Figure 3 for a mapping of county and NYISO load zone to upstate and downstate region. E3 used a variety of data to apportion commercial building square footage, vehicle miles traveled (VMT), and industrial energy usage to upstate and downstate regions; these are described in more detail in the chapter sections on each sector.

Figure 3. Mapping of NYISO load zones, downstate region, upstate region



Source: NYISO[15] for zonal and county mapping, and Table 1 for mapping of counties to upstate/downstate region

Table 1. Mapping of New York State counties to upstate/downstate regions

County	Region	County	Region
Albany County	Upstate	Niagara County	Upstate
Allegany County	Upstate	Oneida County	Upstate
Bronx County	Downstate	Onondaga County	Upstate
Broome County	Upstate	Ontario County	Upstate
Cattaraugus County	Upstate	Orange County	Downstate
Cayuga County	Upstate	Orleans County	Upstate
Chautauqua County	Upstate	Oswego County	Upstate
Chemung County	Upstate	Otsego County	Upstate
Chenango County	Upstate	Putnam County	Downstate
Clinton County	Upstate	Queens County	Downstate
Columbia County	Upstate	Rensselaer County	Upstate
Cortland County	Upstate	Richmond County	Downstate
Delaware County	Upstate	Rockland County	Downstate
Dutchess County	Downstate	St. Lawrence County	Upstate
Erie County	Upstate	Saratoga County	Upstate
Essex County	Upstate	Schenectady County	Upstate
Franklin County	Upstate	Schoharie County	Upstate
Fulton County	Upstate	Schuyler County	Upstate
Genesee County	Upstate	Seneca County	Upstate
Greene County	Downstate	Steuben County	Upstate
Hamilton County	Upstate	Suffolk County	Downstate
Herkimer County	Upstate	Sullivan County	Upstate
Jefferson County	Upstate	Tioga County	Upstate
Kings County	Downstate	Tompkins County	Upstate
Lewis County	Upstate	Ulster County	Downstate
Livingston County	Upstate	Warren County	Upstate
Madison County	Upstate	Washington County	Upstate
Monroe County	Upstate	Wayne County	Upstate
Montgomery County	Upstate	Westchester County	Downstate
Nassau County	Downstate	Wyoming County	Upstate
New York County	Downstate	Yates County	Upstate

Source: E3 assumption for mapping of counties to upstate/downstate region

To estimate demand for energy services over time, E3 first developed activity drivers which drive energy services demand; these activity drivers include projections for population, housing units, building square footage, and VMT. Population and housing unit data for the first simulated year were obtained from the US Census American Community Survey (ACS),[16] while growth rates for population and housing units were set to match population growth obtained from the Cornell Population Center Program on Applied Demographics forecast for New York State population by county.[17] For more details on forecasting of activity drivers for the buildings sector, see Section 5.1. Projections of VMT were obtained from NYSDOT,[13] and growth rates for forecasted years were modified; for more details on the VMT forecasting methodology used in this study, see Section 4.1. The initial population, housing units, commercial square footage, and VMT and their growth rates statewide, upstate, and downstate are presented in Table 2.

Table 2. Activity drivers statewide, upstate, and downstate

Driver	Initial value (2015)	Compound annual growth rate (CAGR)
STATEWIDE		
Population (million)	19.81	0.19%
Housing Units (million)	7.23	0.19%
Commercial Square Footage (billion sq. ft)	5.54	0.44%
Transportation VMT (billion)	121.9	Variable: see Transportation section
DOWNSTATE REGION		
Population (million)	13.74	0.31%
Housing Units (million)	4.75	0.31%
Commercial Square Footage (billion sq. ft)	3.84	0.62%
Transportation VMT (billion)	64.8	Variable: see Transportation section
UPSTATE REGION		
Population (million)	6.07	-0.08%
Housing Units (million)	2.48	-0.08%
Commercial Square Footage (billion sq. ft)	1.70	0%
Transportation VMT (billion)	57.1	Variable: see Transportation section

Sources:

Initial housing unit values from ACS,[16] initial population and growth rate for population from Cornell forecast, [17] growth rates for housing units set to same value as population. Initial commercial square footage values from population-weighted downscale of CBECS commercial square footage data for Mid-Atlantic region,[18] while growth rate for statewide commercial square footage was calculated by scaling historical (2003-2012 time period) relationship between square footage and population growth rate for Mid-Atlantic region by the projected population growth rate for New York State in this study.[18] Initial source for VMT forecasts from NYSDOT,[13] and projections are discussed in Section 4.

2.2 Scenario inputs and outputs

The scenarios examined in this study examine different strategies to achieve substantial economy-wide decarbonization. Key parameters to define the scenarios include, but are not limited to: increasing percentage of electric demand technologies (such as electric vehicles and heat pumps); the usage of low-carbon fuels; the level of non-combustion emissions reductions achieved; the decarbonization of the electric supply portfolio; the penetration of carbon sequestration and negative emission sinks.

For each scenario, results were produced by sector, measure, and year, as follows:

- **Energy**: fuel consumed to provide energy service (e.g., natural gas burned to produce heat, or gasoline burned in vehicles), and fuel consumed by electric generating units to generate electricity
- **Emissions**: GHG emissions, expressed as carbon dioxide equivalent. These include emissions from fuel combustion (calculated by multiplying fuel usage by fuel specific emissions intensities[2]), non-combustion emissions from energy-related sources such as oil and gas systems and non-energy related sources such as industrial processes, waste, and agriculture, and non-combustion greenhouse gas sinks such as the net sequestration of carbon in natural and working lands

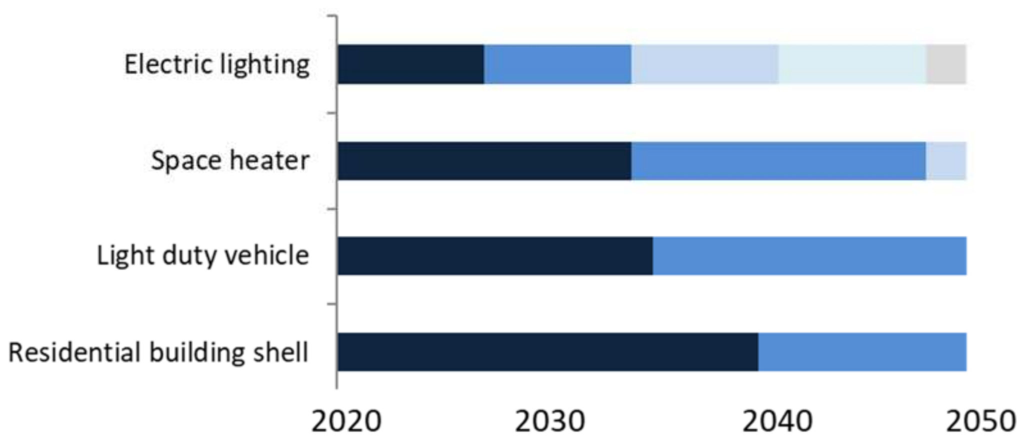
2.3 Projecting energy demand

To characterize GHG emissions from energy consumption, E3 analyzed energy demand using one of two approaches: (1) stock rollover, representing the rollover of appliances and equipment; or (2) total energy, representing the evolution of total energy consumption. The first approach was used when infrastructure data were available from state or federal data sources. Where limited data on stock existed, or data were of poor quality, a total energy approach was used, in which E3 explicitly specified the energy demand by fuel.

2.3.1 STOCK ROLLOVER APPROACH

A stock rollover approach tracks sales and retirements of energy consuming devices while incorporating changes in technology performance, such as efficiency improvements over time. Since it tracks devices being bought and used throughout their lifetimes before being retired, a stock rollover approach accounts for the time lag between changes in annual sales of new devices and change in device stocks over time. For example, if all vehicles sold starting in 2050 are electric, the vehicle fleet in the state will still include other vehicle types in 2050 and later until they are retired. Without a mechanism to drive early retirement of infrastructure before the end of its useful life, there will be a lag between the phase-out of sales and the full turnover of stock, which the stock rollover approach tracks explicitly. Note that different technologies will have different useful lifetimes. Some might have short lifetimes of a few years, like lightbulbs, while others may have longer lifetimes on the order of decades, like building shell systems. The duration of turnover from old to new technology will consist of a ramp up period, in which sales of the new technology increase to their maximum and sales of old technology decrease to their minimum, followed by a phase-out period during which older technology is retired. See Figure 4 for an illustrative graphic of various equipment lifetimes.

Figure 4. Illustrative stock rollover graphic



Source: Illustrative data. Each color represents a stock rollover point in which a technology retires and is replaced with a new one. Note shorter lived technologies, such as, roll over multiple times whereas longer lived technologies, such as building shell, roll over only once in this graphic.

The key analysis step, upon which all other outputs are based, is a calculation of the number of devices or measures of each type in place in each sector and their energy demand (both on-site fuel and electricity) in each year.

Using a stock rollover approach, energy demand in any given year associated with devices introduced in prior years and still in operation is calculated and added to energy demand of newly introduced devices. The energy demanded by these devices is established by multiplying the number of devices from each vintage necessary to supply required energy services with the efficiency factor applicable to each vintage. Devices are retired, or removed from the stock, when they reach their useful life. Every year, sales of new devices are set to a quantity sufficient to replace retiring devices and meet additional growth in demand for energy services. The average efficiency of devices sold each year increases, but a device's efficiency is constant once the device enters the fleet.

2.3.2 TOTAL ENERGY APPROACH

In the total energy approach, the amount of energy use by fuel type is directly input. The analysis accounts for changes in efficiency and fuel switching by allowing the user to specify efficiency and fuel switching parameters for the total fuel consumed, but this methodology does not explicitly track infrastructure turnover in the same way that the stock rollover approach does. As an example, federal and state data sources have limited data on the number, sizes, and efficiencies of airplanes operating within New York State; therefore, E3 represented demand for aviation within New York State by specifying the energy demand for jet fuel explicitly instead of calculating a stock rollover of airplanes.

2.4 Projecting non-combustion emissions

Non-combustion emissions include all GHGs in the emissions inventory that are categorized as non-fuel combustion. This includes emissions from non-energy related categories such as waste, including solid waste decomposition and municipal wastewater; agriculture, including emissions from animals, soils, and manure management; and non-combustion industrial processes, including emissions from refrigerants. In addition, the inventory categorizes emissions associated with incineration of waste and non-fuel combustion emissions from oil and gas systems as non-fuel combustion. Therefore, E3 included incineration of waste and non-fuel combustion in the non-combustion emissions sector. The non-combustion emissions forecasts in this study include the breakdown of categories and greenhouse gas categories as documented in Table 3.

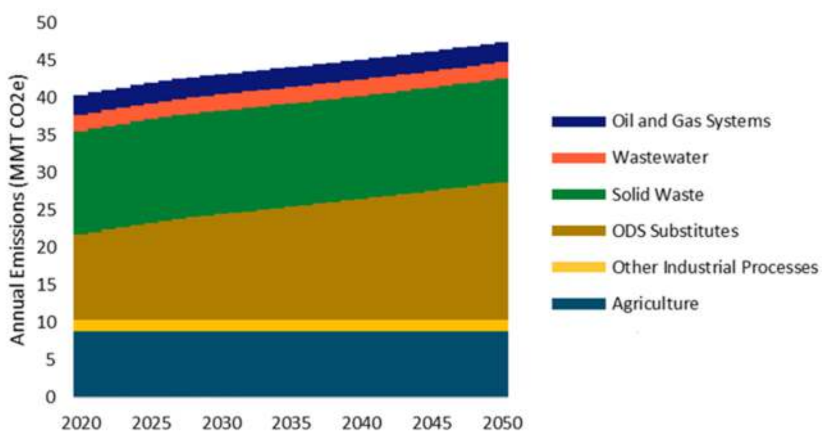
Table 3. GHG emissions characterized by non-combustion category

Non-combustion category	GHG
Solid Waste	
Landfill Decomposition	CH_4
Waste Combustion	CO_2, N_2O
Wastewater	
Municipal Wastewater	CH_4, N_2O
Agriculture	
Agriculture Animals	CH_4
Manure Management	CH_4, N_2O
Agriculture Soils	N_2O
Industrial Processes	
Aluminum Production	PFC, CO_2
Cement Manufacture	CO_2
Electricity Transmission and Distribution	SF_6
Electronics Manufacturing*	HFC, PFC, SF_6, and NF_3
Iron and Steel Production	CO_2
Limestone and Dolomite Use	CO_2
Ozone Depleting Substances (ODS) Substitutes	HFC
Soda Ash	CO_2
Oil and Gas Systems	
Oil and Gas Systems	CH_4

Notes:
*Formerly categorized as 'Semiconductor Manufacturing' in New York State GHG inventory.
Source: New York State GHG inventory.[2]

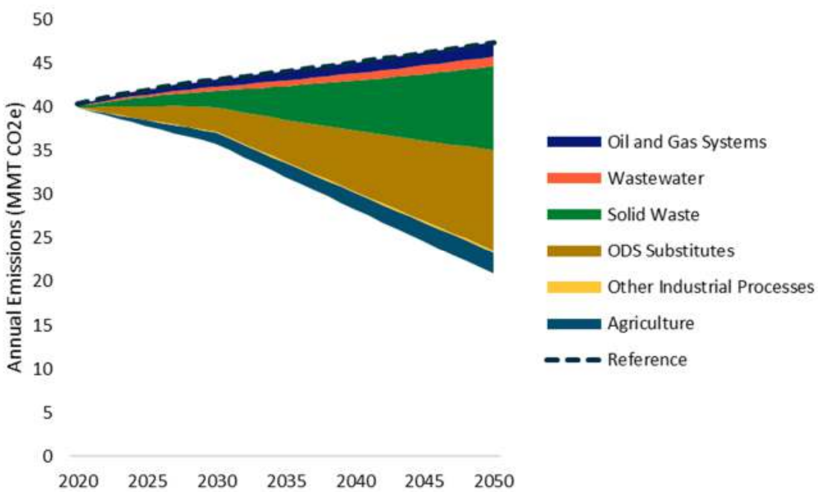
NYSERDA provided E3 with forecasts of non-combustion emissions for all scenarios;[19] these included one reference forecast of non-combustion emissions by source type reflecting business as usual projections, and two Decarbonization Pathways scenarios, which were used in the High Technology Availability and Limited Non-Energy pathways, and which achieve significant non-combustion emissions reductions based on high-level projections of the timing and scale of mitigation. Emissions from the Reference scenario are graphed in Figure 5, while the emissions reductions from the two Decarbonization Pathways scenarios are graphed in Figure 6 and Figure 7. These figures show the reference scenario emissions increasing over time, as well as the reduction in emissions by non-combustion category in the Decarbonization Pathways scenarios. Significant reductions are forecasted across non-combustion emissions sources, which include landfills, farms, industrial facilities, and natural gas infrastructure. Mitigation of short-lived climate pollutants is key, with a focus on methane mitigation and climate-friendly refrigerants, such as Ozone Depleting Substances (ODS) Substitutes. Identification of specific technological opportunities to reduce such emissions is beyond the scope of this report but will be the subject of further analysis.

Figure 5. Non-combustion emissions: Reference scenario



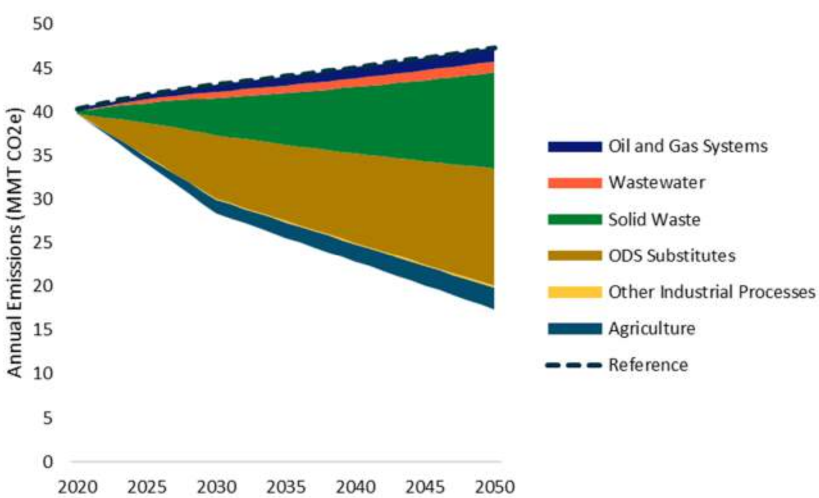
Source: Data from personal communication with NYSERDA.[19]

Figure 6. Non-combustion emissions reductions: Limited Non-Energy Pathway scenario



Source: Data from personal communication with NYSERDA.[19]

Figure 7. Non-combustion emissions reductions: High Technology Availability Pathway scenario



Source: Data from personal communication with NYSERDA.[19]

2.5 Energy supply

As noted above, in the modeling framework for this study E3 calculated the demand for various types of fuels including fossil fuels, bioenergy and low-carbon fuels, and electricity.

2.5.1 FOSSIL FUELS

E3 used the AEO as a source of assumptions about fossil fuel deliverability to New York and used emissions factors for fossil fuels from the NYSERDA Patterns and Trend report. The CLCPA requires additional reporting of emissions associated with "extraction and transmission of fossil fuels imported into the state," as well as the adoption of a 20-year global warming potential to measure the impacts of short-lived climate pollutants[iv] such as methane.[1] Future decarbonization pathways analysis will align statewide GHG emissions accounting with these CLCPA provisions.

2.5.2 BIOENERGY AND LOW-CARBON FUELS

E3 assumed a limited amount of bioenergy was available to mitigate emissions. The availability of bioenergy was limited by biomass feedstock and conversion pathways to convert biomass feedstock to different bioenergy fuels. In addition to bioenergy, E3 assumed other low-carbon fuels (specifically liquid and gaseous hydrogen) were available to displace fossil fuel use. Hydrogen was assumed to be produced via electrolysis. For more details on the feedstock screening and the conversion pathways for bioenergy, as well as details on the hydrogen electrolysis assumptions, see Section 6.

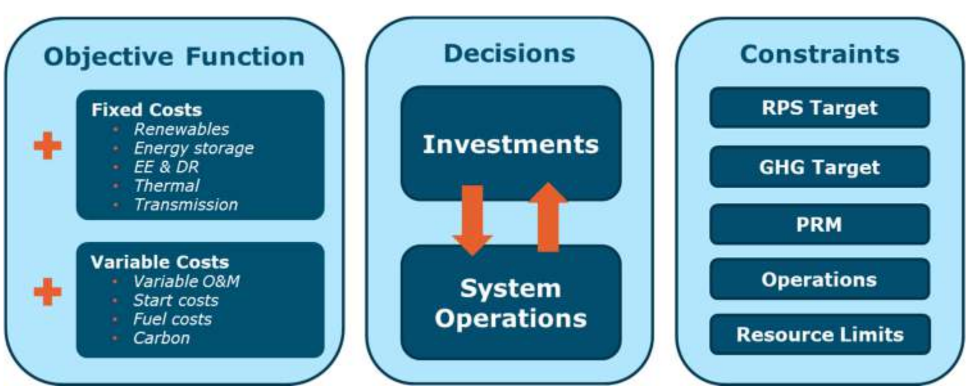
[iv] Short lived climate pollutants are GHGs with high global warming potentials but much shorter lifetimes than carbon dioxide. Main short lived climate pollutants are black carbon, methane, ozone, and fluorinated gases such as hydrofluorocarbons, which are ozone depleting substance substitutes.

2.5.3 ELECTRICITY

Electricity demand was calculated using the New York PATHWAYS model, and E3 used the RESOLVE model to simulate how the electricity generation sector met demand for electricity over time. RESOLVE is an investment and operational optimization model designed to inform long-term planning questions around integrating high levels of renewable energy in electricity systems. RESOLVE co-optimizes investment and dispatch of electricity system components over a multi-year horizon for a study area, including renewable resources as well as complementary resources such as new combined cycle and combustion turbine plants and plant retrofits, and various energy storage technologies.

Designed specifically to address capacity expansion questions for systems seeking to integrate large quantities of variable resources, RESOLVE layers capacity expansion logic on top of a production cost model to determine the least-cost investment plan, accounting for both up-front capital costs of new resources and variable costs of operating the grid reliably over time. In an environment in which most new investments in the electric system have fixed costs significantly larger than their variable operating costs, this type of model provides a strong foundation for identifying potential investment benefits associated with alternative scenarios. For more details, see Section 8, Electricity generation.

Figure 8. RESOLVE analysis overview



2.6 Carbon sequestration

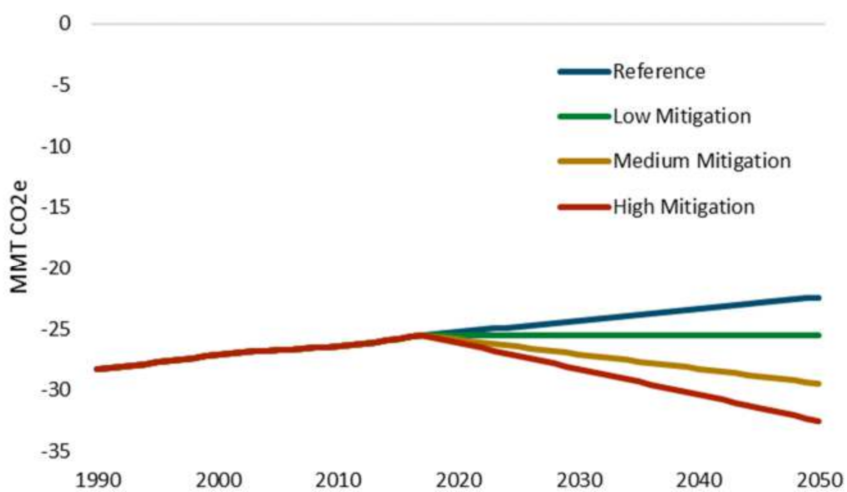
E3 characterized five mitigation options that sequester carbon: natural and working lands (NWL); carbon capture and storage (CCS) in industrial applications, bioenergy with CCS (BECCS), and CCS in the electric sector; as well as direct air capture (DAC).

2.6.1 NATURAL AND WORKING LANDS

A potentially low-cost carbon abatement strategy is to cultivate natural and working lands so as to increase carbon uptake; this strategy can be more cost effective than other strategies such as BECCs and DAC.[20,21]

Historical natural and working lands sequestration levels for New York were developed by E&S Environmental Chemistry based on USDA Forest Service data, in a report for NYSERDA,[22] while projections were based on both historical trends and analysis by a NYSERDA-NYSDEC interagency working group with input from subject matter experts.[19] E3 included multiple levels of natural and working lands sinks in this study, ranging from a reference scenario to a high sequestration scenario. See Figure 9 for the forecasted sizes of these sinks.

Figure 9. New York State annual net natural and working lands carbon emissions



Source: Data from email communication with NYSERDA.[19]

2.6.2 CARBON CAPTURE AND STORAGE

Carbon capture and storage (CCS) is a process that captures CO_2 emissions from sources industrial processes and natural gas fired power plants and either reuses or stores it so that it will not enter the atmosphere. Based on data from a draft report on CCS in New York, prepared for NYSERDA by Navigant,[23] E3 estimated the storage potential for CO_2 as 40 to 90 MMT CO_2/yr; see Table 4. This estimate is for the potential flux of CO_2 which can be stored and is greater than the amount of CCS used in the scenarios in this study.

Table 4. CO_2 storage potential

Storage type	Potential storage estimate (MMT CO_2/year)
Onshore only (saline formations)	40
Onshore and offshore (saline formations)	130 (40 from onshore, 90 from offshore)
Source: Data from draft report prepared for NYSERDA by Navigant[23]	

The remainder of this section discusses the characterization of CCS as a mitigation option within industry, for bioenergy production, and in the electric sector.

2.6.2.1 Industry CCS

For some industrial applications post-combustion CCS can be a relatively inexpensive strategy to reduce GHG emissions. CCS might be cheaper per energy unit than renewable electricity or hydrogen. Technical assessments view geologic sequestration of captured CO_2 as a sound long-term storage option with little risk of CO_2 leaking back to the atmosphere. The amount of New York state industrial CCS potential included in this study is documented in Table 5.

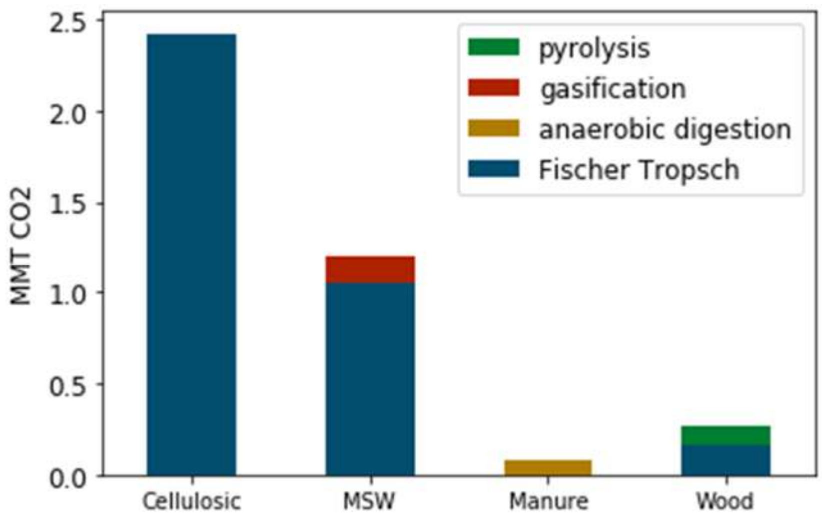
Table 5. Industry CCS capture potential

Carbon source	2050 CO_2 capture potential (MMT CO_2/year)	Reference & assumptions
Natural gas combustion	1.38	Draft report + Rubin et al. 2015[24]
Aluminum smelter	0.32	Draft report + E3 reporting
Scrap-based steel mill	0.14	Draft report + E3 reporting
Glass production	0.09	Draft report
Total	**1.92**	**See above**
Sources: Capture and storage paper by Rubin et al.,[24] Draft report prepared for NYSERDA by Navigant.[23]		

2.6.2.2 Bioenergy with CCS (BECCS)

In assessing the carbon emissions from advanced biofuels, E3 assumed that directly combusting an advanced biofuel is carbon neutral, as the carbon absorbed in growing fuel feedstock is offset by the carbon emitted in combusting the refined fuel product. In scenarios with biofuel usage, capturing and storing the carbon emitted from biofuel refining would result in a net GHG sink as the GHG emitted in combusting the refined fuel product is less than the GHG stored in growing the feedstock and in capturing the carbon emitted in the refining process. E3 estimated the potential for bioenergy with CCS in an in-state biorefinery; the feedstock which is applicable to enter an in-state biorefinery is municipal solid waste (MSW), and agricultural resources. In addition to these in-state BECCS eligible feedstocks, E3 assumed in-state landfill gas and wastewater treatment plants (WWTP) would yield an additional amount of biomass feedstock that, when passed through the BECCS process, would sequester 0.1 MMT CO_2. E3 estimated the potential CO_2 abatement from BECCS in the Decarbonization Pathways scenarios as seen in Figure 10.

Figure 10. BECCS potential carbon abatement in 2050 (plus 0.1 MMT from in-state landfill gas and wastewater treatment plants)



Source: E3 analysis of potential carbon abatement of in-state MSW and agricultural feedstock from federal report[25] on biomass feedstocks, and additional landfill gas and WWTP feedstock from NYSERDA report.[26]

2.6.2.3 Electric sector CCS

E3 assessed natural gas combined cycle power plants with CCS as a candidate resource in the electric sector analysis, as described in Section 8.

2.6.3 DIRECT AIR CAPTURE

DAC systems capture CO_2 directly from the air and perform a series of processes to sequester it. In most forms of DAC, CO_2 is captured into a separating agent that must later be regenerated with heat and/or water, releasing a pure stream of CO_2 for subsequent utilization or storage. CO_2 capture is the costliest part of the CCS process with post-combustion capture. CO_2 storage is based on the same trapping mechanisms that have stored hydrocarbons deep underground for centuries.

While the technical potential for capturing and sequestering carbon from the air is high in theory, there is substantial uncertainty regarding the cost, efficiency, and ability of DAC technologies to achieve scale in the future. As the United Kingdom Royal Society noted in a research paper on greenhouse gas removal technologies, current DAC systems range in technology readiness levels from bench-scale research to active commissioning.[21]

DAC systems require significant energy input including electricity and heat. Since the concentration of CO_2 in the air is much smaller than the concentration of CO_2 in a typical post-combustion gas, the amount of electricity and heat required to perform DAC is higher than that for post-combustion capture. The thermodynamic minimum for a DAC system is about 0.2 MWh/tCO_2 but in practice E3 estimate the electricity demand would be at least five times higher; in this study every metric ton of CO_2 captured by DAC created a 1-MWh load. [21,27] This load, as with all electricity load, was analyzed within the RESOLVE optimal capacity expansion and dispatch model. The DAC load was assumed to have average capacity factor of 25% over the course of the year and no minimum load requirements. This allowed for flexibility in the system, ensuring that DAC systems were dispatched in a manner that was timed so as not to cause incremental peak electricity impacts without assigning them unrealistically high load flexibility capabilities. E3 assumed the heat necessary for the capture process was provided by natural gas combustion with the carbon captured through a post combustion carbon capture system.

3 Buildings

3.1 Analysis approach

This section describes the approach used to analyze energy demand and emissions associated with residential and commercial buildings in New York. The buildings sector in this study is subdivided into residential and commercial end use device types; industrial building energy is included under the industrial sector.

E3 benchmarked the initial simulated year (2015) GHG emissions from buildings to emissions from the residential and commercial sectors in the NYSERDA GHG inventory, and benchmarked simulated energy demand by fuel to fuel demand in the residential and commercial sectors in *Patterns and Trends*.[11] The *Patterns and Trends* report includes fuel usage for residential and commercial buildings in New York, obtained from the EIA State Energy Data System (SEDS).[28] SEDS uses a variety of survey data to estimate energy consumption by sector. SEDS does not define a single buildings sector, defining both residential and commercial sectors separately. SEDS defines the residential sector as including living quarters for private households, while the commercial sector consists of service-providing facilities and equipment of businesses, governments, and other private and public organizations, including institutional living quarters. Common energy demand for both residential and commercial buildings include space conditioning, water heating, lighting, refrigeration, cooking, and a variety of other appliances.

The analysis performed for this study accounted for major differences in segmentation between residential and commercial buildings. However since SEDS and *Patterns and Trends* data do not specify whether residential households within multi-use buildings would be categorized within the commercial or residential sector, this study reports energy consumption and greenhouse gas emissions for residential and commercial buildings as one sector.

E3 calculated buildings sector energy demand by breaking down energy demand into residential and commercial end use device types which provide distinct energy services and analyzing the energy demand of these distinct end use devices. As an example, the annual energy demand for domestic hot water is the amount of fuel residential water heaters consume every year, while the energy services demand for residential water heating is the amount of hot water of a certain temperature which residences demand, regardless of water heater fuel type or efficiency of the technology delivering the hot water.

Energy demand for devices, in categories applying the stock rollover approach, was calculated by summing the energy demand for every end use device technology. In each simulated year, E3 calculated energy demand for each end use device technology by multiplying the energy service demand by the inverse of device efficiency. For example, if a residential household demanded 35 units of hot water per year and a natural gas water heater has an efficiency of 0.8 units of hot water output per unit of input natural gas, the demand for natural gas for water heating would be 35 * (1/0.8) = 43.75 units of natural gas. The stock rollover approach tracks the lifetimes and efficiencies of the fleet of devices within each end use device type and calculates the energy demand by summing the energy demand for each constituent end use device. For end uses where the total energy approach was applied, E3 characterized energy demand by fuel type directly based on scenario-specific user inputs characterizing energy efficiency, potential for electrification, and potential for switching from fossil fuel combustion to low-carbon fuel combustion.

E3 simulated building energy and emissions based on data available from NEMS and the NYSERDA *Residential Statewide Baseline Study*.[29] See Table 6 for a list of the end-use device category and the analysis approach used. Note that residential space heating was broken into different size classes to account for the differences in space heating demand by household size. This distribution was assumed to remain constant in future years – i.e., the portion of small single-family homes in the upstate region is constant as the total number of households evolves. For all other end uses, service demand was not differentiated for different household types.

The simulated building energy demand for the first simulated year was benchmarked to residential and commercial energy demand by fuel from the *Patterns and Trends* report. The "Commercial District Heat" end use device type represents the heat demand for district heat located in New York City. A district heat system is one in which a central plant provides steam or hot water, pumped through a series of pipes to connected nearby buildings to provide space heating and/or hot water needs.[30] The New York City district heat system is a complex energy system itself, but without more information about the steam producing units within this system, E3 used a total energy approach to analyze heat produced by the district heat system. The "Residential Other" and "Commercial Other" end use device types were characterized using the total energy approach to benchmark energy demand by fuel to account for all other energy demand within the residential and commercial buildings which do not appear in other end use device types. For example, residential televisions and computers demand electricity but their electricity demand were calculated within the "Residential Other" end use device type as E3 did not have detailed information on the number, efficiency, and usage patterns of televisions and computers within the state.

Table 6. Buildings end-use device types and analysis approach

Building category	End use device type	Analysis approach
Residential	Central Air Conditioning	Stock Rollover
	Room Air Conditioning	Stock Rollover
	Building Shell	Stock Rollover
	Clothes Drying	Stock Rollover
	Clothes Washing	Stock Rollover
	Cooking	Stock Rollover
	Dishwashing	Stock Rollover
	Freezing	Stock Rollover
	Reflector Lighting	Stock Rollover
	General Service Lighting	Stock Rollover
	High Intensity Discharge Lighting	Stock Rollover
	Linear Fluorescent Lighting	Stock Rollover
	Refrigeration	Stock Rollover
	Space Heating: Single Family	Stock Rollover
	Space Heating: Townhomes and Small Multifamily	Stock Rollover
	Space Heating: High-rise Multifamily	Stock Rollover
	Water Heating	Stock Rollover
	Residential Other	Total Energy
Commercial	Air Conditioning	Stock Rollover
	Cooking	Stock Rollover
	General Service Lighting	Stock Rollover
	High Intensity Discharge Lighting	Stock Rollover
	Linear Fluorescent Lighting	Stock Rollover
	Refrigeration	Stock Rollover
	Space Heating	Stock Rollover
	Ventilation	Stock Rollover
	Water Heating	Stock Rollover
	District Heating	Total Energy
	Commercial Other	Total Energy

The allocation of number of residential households in the upstate and downstate regions was based on mapping the number of residential households within the counties in the upstate and downstate regions, with data on households within each county obtained from ACS 2015 housing characteristics.[16] See Table 1 for the mapping of county to upstate and downstate region used in this study.

To further analyze residential space heating demand, E3 categorized space heaters according to building type: single family, small multi-family buildings, and high-rise multi-family buildings. The methodology used to categorize residential building types from ACS 2015 residential building data is specified below, and yields a segmentation of households as specified in Table 7.

+ Households within ACS building type '1 detached' are categorized as 'Single family' in this study
+ Households within ACS building type of '10 or more apartments' in Manhattan (New York Country) is considered as 'High-rise multifamily' in this study*
+ Households in all other ACS building categories are categorized as 'Small Multifamily' in this study

This analysis assumed that most '10+ apartment' buildings in Manhattan are high-rise buildings. This may overestimate some high-rise buildings, but since this categorization did not consider high-rise buildings in other parts of New York City, this overestimate may be offset by the unaccounted-for high-rise buildings in other boroughs of New York City and the downstate region. Similarly, this analysis assumed there are no high-rise buildings in the upstate region; while this is an underestimate, the impact on simulated energy demand was likely minor. The purpose of categorizing residential households into building types was to capture differences in heating demand per household. The largest difference in heating demand per household is between a single family detached home and a household in an apartment building: the difference in space heat demand per household in small and large apartment buildings is relatively smaller and has less impact on heating load per household than the difference between multifamily and single family.[31]

Table 7. Calculation of space heating household type in PATHWAYS, based on aggregation of households within building types in ACS

ACS building type	PATHWAYS residential building type for space heating demand calculation	Households within downstate region	Households within upstate region
All	Total households	4,751,674	2,482,020
'1 detached'	Households in single family buildings	1,406,402	1,686,440
'10 or more apartments' in Manhattan	Households in high-rise multifamily buildings	671,612	-
All others	Households in small multifamily buildings	2,674,843	795,116
Source: Data on number of households from ACS 2015 data,[16] with categorization of households into the three building types identified in this table based on E3 categorization of households within ACS building types to category of residential building type analyzed in this study.			

In residential buildings, E3 calculated the total number of devices within an end use device type (e.g., the total number of clothes washers, or total number of space heaters) from EIA NEMS input data files and documentation for the Mid-Atlantic region.[10] These data include the number of devices within an end use device type for the Mid-Atlantic region, and the number of households within the Mid-Atlantic region; using these data E3 estimated the number of devices per household for each end use device type (e.g., number of space heaters per housing unit) within New York state; this factor, the number of devices per household, can be found in Table 8.

Table 8. Number of devices per end use device type per housing unit

Sector	End use device type	Stock per housing unit*
Residential	Central Air Conditioning	0.42
	Room Air Conditioning	0.92
	Building Shell	1
	Clothes Drying	0.64
	Clothes Washing	0.70
	Cooking	0.79
	Dishwashing	0.97
	Freezing	0.54
	Reflector Lighting	0.25
	General Service Lighting	3.40
	Exterior Lighting	15.80
	Linear Fluorescent Lighting	2.11
	Refrigeration	0.77
	Space Heating: Single Family	1.01
	Space Heating: Townhomes and Small Multifamily	0.92
	Space Heating: High-rise Multifamily	0.92
	Water Heating	0.98
Commercial	All end use device types	n/a – analyzed square footage and energy service demand per square footage

Notes:

*For most end use device types this stock per housing unit is applied to all the housing units within the region. For residential space heaters, it is applied to the specific building type in the first year. For example, since there are no simulated high-rise multi-family residential household types in the upstate region, multiply 0.92 units/household * 0 households to calculate 0 space heaters for high-rise multifamily units in the upstate region.

Source*:* EIA NEMS input data[10] and technical documentation[32,33]

With greater variability in commercial building types, the unit of stock within the commercial stock rollover end use device types is a commercial square foot, rather than an estimate of number of devices. For example, a commercial space heater would be characterized as heating one square feet of commercial building space. This commercial space heater would have an associated efficiency and lifetime. At the end of the useful life of this space heater, the heater is retired and replaced with a new space heater with a different efficiency. In this way the commercial space heater stock rollover is similar to the stock rollover of residential space heaters, but instead of calculating the unit of stock as each individual space heaters, the unit of stock is each square foot of commercial building space. The purpose of this stock rollover approach, as opposed to using average energy use across all commercial square feet, is to maintain the advantages of a stock rollover approach in capturing the lifetime of device equipment, efficiency improvements of device equipment, and allowing the user to track the time lag of implementing new energy policy.

In the residential stock end use device types, calculating the distribution of devices by fuel or technology type was based on data obtained from the *Residential Statewide Baseline Study*[29] where available. For example, the *Residential Statewide Baseline Study* includes data on the proportion of residential housing units which use different heating technologies for space heating (e.g., cordwood stoves, natural gas furnaces, electric resistance heaters); these data were used to calculate the initial distribution of space heating technology types. The *Commercial Statewide Baseline Study* was not yet complete at the time of this study, so E3 used the distribution of fuel and technology types from EIA NEMS data, which includes a distribution of devices by fuel and technology type for the Mid-Atlantic region as a whole.

Note that EIA NEMS data were obtained, in part, from the federal Commercial Buildings Energy Consumption Survey (CBECS)[18] and Residential Energy Consumption Survey (RECS).[34] The most recent comprehensive data from these surveys are available from survey years 2012 and 2015 respectively; this is because the surveys are not performed every year, and there is a delay of 3-4 years between survey completion and detailed public data availability. Thus, the most recent CBECS was performed in 2012, with detailed data published in 2016, while the most recent RECS was performed in 2015, with detailed data published in 2018.

E3 sourced technology efficiencies for existing installed technologies from the 2015 RECS and 2012 CBECS, while projected appliance efficiencies were sourced from reports on building appliance efficiencies and costs prepared for the EIA.[35] These reports include two forecasts of technology efficiency for energy consuming devices: a "Reference" and an "Advanced" case. The reports consider currently published efficiency standards and regulations, with efficiency ranges given to represent the typical span of a parameter, not necessarily the absolute highest or lowest available on the market. The "Advanced" case forecasts assume increased market incentive and federal research and development, and are meant to include developed but not commercialized product changes; incremental improvements expected due to increased research and development; and increased adoption of high efficiency devices due to market incentives. The "Advanced" case does not include technologies emerging in preliminary research, prototypes, or devices which have only been demonstrated in theoretical calculations.

Device technology efficiencies were taken from the "Reference" case forecasts, with deviations for certain technologies with particularly sensitive performance characteristics, specifically residential heat pumps. The device-specific efficiencies are forecast to improve over time due to improvements in device manufacturing and existing policies such as federal efficiency standards. Note device efficiency units, different for each end use device type, are defined in Table 9.

Table 9. Efficiency units for building devices

Efficiency unit	Definition	End use device type
CoP	Coefficient of Performance, or the ratio of useful energy produced per unit of input energy	Commercial: Refrigeration; Residential and Commercial: Air Conditioning, Cooking, Space Heating, Water Heating
kWh/lb	Amount of electricity required to dry one pound of clothes	Residential: Clothes Drying
n/a	Some end use device types do not contain efficiency data in NEMS and instead report direct final energy demand	Residential: Dishwashing, Freezing, Refrigeration; Residential and Commercial: Building Shell, Other Commercial: District Heating
Lumens/Whr	Lumens of light output per Whr of electricity input	Residential and Commercial: Lighting
CFM-hr/BTU	Cubic Foot Minute – hours of air exchange per BTU input	Commercial: Ventilation

To calculate energy service demand by end use device type, E3 relied primarily on EIA NEMS input data. However, these service demand data in NEMS were calculated across the entire Mid-Atlantic region so additional data sources were used to further refine the energy service demand per end use device type; these data sources included RECS[34] and CBECS,[18] NYSERDA data on space heating service demand sourced from two NYSERDA reports on space heating and heat pumps, [31,36] as well as benchmarking energy demand by fuel to NYSERDA *Patterns and Trends.*[11] Energy service demand were differentiated between housing type for heating appliances as smaller homes require less energy service demand for heating than larger homes. While there may be energy service demand differences across home size for other end use device types as well, with limited data on this distinction being available E3 characterized energy service demand for other end use device types as being independent of household size. Table 10 reports the energy services demand per device for the upstate and downstate regions.

Note for a few residential end use device types (Clothes Washing, Dishwashing, Freezing, and Refrigeration), NEMS documentation reports energy demand per device directly, with no intermediate energy service demand variable. Thus, instead of calculating an implied energy demand by combining data on service demand and device efficiency separately, E3 used the NEMS reported energy demand by device for these end use device types. This approach still allows for stock tracking and calculates the lag in both device efficiency improvements and in the stock rollover of devices over time. The “Building Shell” end use device type did not demand energy service; it affected the service demand of other end use device types because an efficient shell reduces energy service demand for space heating and space cooling. For further details on the effects of building shell on other end use device types’ energy demand, see Section 3.2.1.

Table 10. Representation of building service demand by end use device type

Sector	End use device type	Service demand per device (upstate)	Service demand per device (downstate)
Residential	Central Air Conditioning	16.13 (MMBtu of cooling)	14.99 (MMBtu of cooling)
	Room Air Conditioning	2.19 (MMBtu of cooling)	2.19 (MMBtu of cooling)
	Building Shell	n/a	n/a
	Clothes Drying	2,433 (lbs/yr)	2,433 (lbs/yr)
	Clothes Washing	n/a	n/a
	Cooking	1.77 (MMBtu of cooking)	1.77 (MMBtu of cooking)
	Dishwashing	n/a	n/a
	Freezing	n/a	n/a
	Reflector Lighting	665 (Lumens – assume 2 hrs/day average usage)	665 (Lumens – assume 2 hrs/day average usage)
	General Service Lighting	774 (Lumens – assume 2 hrs/day average usage)	774 (Lumens – assume 2 hrs/day average usage)
	Exterior Lighting	1,171 (Lumens – assume 2 hrs/day average usage)	1,171 (Lumens – assume 2 hrs/day average usage)
	Linear Fluorescent Lighting	8,758 (Lumens – assume 2 hrs/day average usage)	8,758 (Lumens – assume 2 hrs/day average usage)
	Refrigeration	n/a	n/a
	Space Heating: Large Single family	87 (MMBtu of heating)	68 (MMBtu of heating)
	Space Heating: Small single family and multi-family	65 (MMBtu of heating)	52 (MMBtu of heating)
	Space Heating: High-rise multi-family	0: no high-rise multi-family space heaters analyzed in upstate region	46 (MMBtu of heating)
	Water Heating	11.11 (MMBtu of heating)	9.52 (MMBtu of heating)
	Other	0: total energy approach used, not stock rollover	0: total energy approach used, not stock rollover
Commercial	Air Conditioning	19.80 (kBtu/sq ft)	19.80 (kBtu/sq ft)
	Building Shell	0	0

	Cooking	3.72 (kBtu/sq ft)	3.72 (kBtu/sq ft)
	General Service Lighting	1.08 (thousand Lumen years/sq ft)	1.08 (thousand Lumen years/sq ft)
	High Intensity Discharge Lighting	0.53 (thousand Lumen years/sq ft)	0.53 (thousand Lumen years/sq ft)
	Linear Fluorescent Lighting	21.52 (thousand Lumen years/sq ft)	21.52 (thousand Lumen years / sq ft)
	Refrigeration	18.42 (kBtu/sq ft)	18.42 (kBtu/sq ft)
	Space Heating	26.52 (kBtu/sq ft)	26.52 (kBtu/sq ft)
	Water Heating	6.30 (kBtu/sq ft)	6.30 (kBtu/sq ft)
	District Heating	0: total energy approach used, not stock rollover	0: total energy approach used, not stock rollover
	Commercial Other	0: total energy approach used, not stock rollover	0: total energy approach used, not stock rollover

Note:

Some end use device types in NEMS do not list energy services demand, but list final energy demand by end device. For those end use device types, this table lists "n/a" as the energy services demand unit.

Sources:

EIA NEMS data and model documentation for service demand for non-space heating device types,[10,32,33] NYSERDA reports on space heating and air source heat pumps.[31,36]

3.2 Mitigation options

Improvements in energy efficiency and the electrification of residential and commercial building end-uses were key decarbonization strategies considered in this study. Energy demand that could be met with electric systems in the buildings sector include space heating, water heating, cooking and drying. Fossil fuel demand in buildings is dominated by space heating, water heating, cooking, and clothes drying (in descending order by demand). Electrifying these end uses presents a range of costs and benefits, depending on the location and condition of the building, as well as the type of end use in question.

3.2.1 ENERGY EFFICIENCY AND CONSERVATION

Energy efficiency in buildings can be one of the most cost-effective and commercialized sources of decarbonization available in the economy, and is critical to decarbonizing buildings.[5] However, energy efficiency represents a heterogenous set of measures, some of which are easier to deploy than others. LED lighting for example, is rapidly penetrating the building market, and is achieving energy savings at low to no incremental cost.[37] Improved codes and standards for appliances, including but not limited to refrigerators, clothes washers and dryers, are another source of low-cost energy and carbon savings.

E3 implemented behavioral conservation and building shell improvements to reduce energy services demand across specific end use device types. A behavioral conservation measure reduces energy services demand by a specified percentage from its original value. Building shell improvements (such as deep retrofits of homes) are simulated as decreasing the service demand in HVAC end use device types. Improvements to building shells are harder to deploy because they can incur costly retrofits but are popular with customers because they can improve home and office comfort, as well as reduce energy bills. E3 calculated the stock rollover of building shells with a 20-year lifetime. The penetration of efficient building shells reduced the energy services demand in the HVAC end use device types: an efficient shell reduced demand for air conditioning by 12%, and space heating by 40%.[10] These reduction percentage values are representative of a weighted share of reductions in single family, multi-family, and mobile home housing units. The resulting building shell effect on service demand is a function of efficient shell market penetration.

3.2.2 ELECTRIFICATION OF END USES

In addition to the energy efficiency measures described above, E3 used electrification of various building end uses as a major strategy to decarbonize the buildings sector.

3.2.2.1 Water heating

Water heating technologies include fossil fuel powered water heaters, electric resistance water heaters, and electric heat pump water heaters. Electric resistance water heaters are the mature, prevailing electric technology, but are outperformed by heat pump water heaters which can be more efficient than electric resistance heaters.[38] Given the cost, efficiency, and technology advancements, E3 considered electric resistance water heaters highly likely to be replaced with heat pump water heaters, particularly because these do not require building retrofits. Due to the relatively high energy efficiency of heat pumps for water heating and HVAC, these two end uses represent key targets for electrification in buildings as a replacement for combustion of liquid and gaseous fuels.

3.2.2.2 Cooking, clothes drying, other

Cooking and clothes drying represent smaller opportunities, as the efficiency benefit of electrification is smaller, and their total energy use is also a smaller portion of building energy use. For electrified cooking, some inroads have been made in the high-end market with electric induction cooking. These induction cookstoves could prove to be popular with some consumers due to the higher degree of control in temperature enabled by induction, as well as the health and human safety benefits of electric stoves.[38]

3.2.2.3 Space heating

The technological potential for electric space heating through 2030 is vast; however, the economics can be challenging based on building type, climate, and incumbent fuel. Retrofitting existing homes and buildings with heat pumps might require the need for expensive retrofits to redo duct work, perform electric panel upgrades, and site new outdoor compressors. Integrating heat pumps into new building construction does not incur these retrofit expenses and can also displace the cost of natural gas piping and distribution interconnection. Ductless heat pumps are a relatively nascent technology option that can make retrofits more cost effective in compact building floorplans since they avoid the need for retrofitting ducts.

Space heating technologies include fossil fuel powered furnaces and boilers, air source heat pumps (ASHP), and ground source heat pumps (GSHP). Natural gas furnaces are the prevailing technology in use today, but the efficient electric technologies have improved drastically in price and performance.

Space heating is one of the large drivers of buildings fuel use and switching to electric heat pumps is a core decarbonization strategy. Heat pumps are more efficient at higher outdoor air temperatures, and very cold winter temperatures can cause large spikes in electricity demand or require specialized equipment ("cold climate ASHP") designed to maintain efficiency at colder temperatures.[39] Although cold climate ASHP are more efficient than conventional ASHP at colder temperatures, even cold climate ASHP have performance problems in very cold winter temperatures that can cause increases in electricity demand. E3 characterized GSHP as having an annual CoP of 4.0 and represented various cold climate ASHP technologies as a range of different efficiencies which reflect peak demand but assumed the average annual CoP for all cold climate ASHP were 3.1. The annual average CoP were not varied across building type.

4 Transportation

4.1 Analysis approach

This section describes the approach used to analyze the transportation sector, including the methodology used to forecast energy service demand for transportation, data on vehicle stock and efficiency projections, the methodology used to calculating energy demand for each transportation vehicle category characterized, and options for reducing GHG emissions from transportation.

E3 used a combination of the stock rollover and total energy approaches to analyze the transportation sector. E3 benchmarked GHG emissions from the transportation sector in the first simulated year to the New York State GHG inventory, and compared statewide transportation energy demand by fuel to data obtained from the *Patterns and Trends* report published in January, 2019.[11] The *Patterns and Trends* report includes energy demand for transportation as obtained from the EIA SEDS.[28] SEDS uses a variety of survey data to estimate energy consumption by sector and defines the transportation sector as consisting of all vehicles whose primary purpose is in transporting people or goods; energy demand from vehicles whose primary purpose is not transportation (e.g., cranes and construction equipment, farming vehicles, forklifts) is classified in the sector of the vehicles' primary use.

For most on-road vehicle categories, E3 applied a stock rollover approach, but for non-road vehicle categories a total energy approach was used. See Table 11 for an overview of analysis approach by vehicle category, along with data sources used to forecast energy demand by category in future years.

Table 11. Transportation analysis approach by vehicle category

PATHWAYS vehicle category	Analysis approach	Data sources
Light Duty Autos	Stock Rollover	E3/NYSERDA/NYSDOT
Light Duty Trucks	Stock Rollover	E3/NYSERDA/NYSDOT
Medium Duty Trucks	Stock Rollover	E3/NYSERDA/NYSDOT
Heavy Duty Trucks	Stock Rollover	E3/NYSERDA/NYSDOT
Buses	Stock Rollover	E3/NYSERDA/NYSDOT
Aviation	Total Energy by Fuel	GHG Inventory/EIA
Transportation Other*	Total Energy by Fuel	GHG Inventory/EIA

Note:

*Transportation Other includes other demand not captured in the stock rollover vehicle categorization, including motorcycles, recreational boats, and other on-road and non-road demand

The unit of energy service demand for vehicle categories simulated with a stock rollover approach in transportation (Light Duty Autos, Light Duty Trucks, Medium Duty Trucks, Heavy Duty Trucks, and Buses) is VMT. As E3 used a total energy approach for calculating energy demand and associated GHG emissions in the non-stock vehicle categories (Aviation, Transportation Other), there is no fundamental energy service demand driver which is separate from energy demand for these non-stock vehicle categories.

E3 analyzed the energy demand of the upstate and downstate regions separately. For vehicle categories analyzed with a stock rollover approach, E3 calculated county level stock data and VMT demand using data provided by NYSERDA and the NYSDOT;[13] for further discussion of the VMT forecasting approach see 4.1.1.

For the non-stock vehicle categories, E3 relied on a variety of data sources to benchmark energy demand in the first simulated year. For aviation, E3 benchmarked jet fuel demand by benchmarking calculated jet fuel emissions to aviation emissions as reported in the GHG inventory, which reports jet fuel emissions which the State is responsible for. The current inventory accounting framework assigns New York State responsibility for 70% of the emissions which would arise from combusting jet fuel sold within the state, and assuming that New York State is not responsible for emissions associated with combustion of international bunker fuel sold within the state.[2] As noted in Table 11 *Patterns and Trends* categorizes the transportation sector in the same way as SEDS does, in which transportation is defined as all vehicles whose primary purpose is transporting people or goods.

After accounting for energy demand and associated emissions from the stock rollover vehicle categories and aviation, the remainder of fuel demand needed to benchmark transportation sector fuel demand to the *Patterns and Trends* report was allocated to the "Transportation Other" vehicle category; these include but are not limited to motorcycles, ports, rail, recreational boats, and other on-road and non-road demand. E3 allocated the energy demand for the vehicle categories simulated with a total energy approach to the upstate and downstate regions by scaling the statewide energy demand by the appropriate upstate/downstate human population. This is summarized in Table 12.

Table 12. Transportation geographic allocation (upstate/downstate) methodology

PATHWAYS vehicle category	Initial allocation variable	Explanation
Light Duty Autos Light Duty Trucks Medium Duty Trucks Heavy Duty Trucks Buses	Vehicle fleet by county	Stock rollover: Using stock data by county from NYSDOT, E3 analyzed the 2015 stock distribution of each of these vehicle categories. The NYSDOT stock distribution data was provided for 2017 and E3 backcasted the vehicle stock to 2015 using human population growth rate between 2015 to 2017.
Aviation Transportation Other	Human population	Total energy demand by fuel data is available at a statewide level, and this energy demand by fuel was downscaled to the upstate/downstate regions by the human population within each region in 2015.
Sources: Vehicle fleet data by county from NYSDOT,[13] human population by county from Cornell.[17]		

To forecast energy demand from the vehicle categories analyzed using a stock rollover approach, E3 required characteristics of the existing vehicle stock within the state including the number of vehicles, the fuel efficiencies and lifetimes of vehicles, the VMT per vehicle, as well as projections of future vehicle efficiencies and lifetimes. These data were obtained from E3 analysis of variety of data including federal NEMS and AEO data,[10,40] NYSDOT projections,[13] the NREL *Electrification Futures Study.*[41]

Vehicle efficiency values were obtained primarily from NEMS. For most vehicles E3 used efficiency improvements provided in the AEO 2019 Reference scenario, which included improvements in the Corporate Average Fleet Efficiency (CAFE) standards through vehicular model year 2026.[40] For light duty and heavy duty electric vehicles (EV) E3 obtained efficiency projections from the NREL *Electrification Futures Study.*[41]

Table 13 reports the number of vehicles and annual VMT per vehicle for upstate and downstate regions in 2015. E3 assumed that the growth rate in vehicle stock (number of vehicles) was identical to the population growth rate in the upstate/downstate regions. These population growth rates were sourced from county-level population projections from Cornell,[17] which were then aggregated into the appropriate upstate/downstate categories following the county zone mapping shown in Table 1. The VMT per vehicle value was varied by year to ensure that simulated fleet VMT benchmarked to fleet VMT projections; the fleet VMT projection methodology is described in Section 4.1.1.

Table 13. Vehicle stock and VMT per vehicle in 2015

PATHWAYS vehicle category	Downstate vehicle stock (thousand vehicles)	Downstate annual average VMT per vehicle (miles/vehicle)	Upstate vehicle stock (thousand vehicles)	Upstate annual average VMT per vehicle (miles/vehicle)
Light Duty Autos	2,444	11,364	1,681	13,116
Light Duty Trucks	3,366	9,962	2,696	11,386
Medium Duty Trucks	97	18,680	78	21,821
Heavy Duty Trucks	24	47,094	35	63,234
Buses	27	22,005	15	29,854
Source: E3 analysis of NYSDOT data.[13]				

4.1.1 VMT FORECASTING METHODOLOGY

This section describes the forecasting methodology used to calculate VMT demand in this study. In brief, E3 used NYSDOT forecasts for VMT of freight vehicles, and modified the NYSDOT VMT growth rates for light duty vehicles (LDV) as E3 believed the original NYSDOT forecasts were inconsistent with the population growth forecast assumed in this study.

In calculating vehicular emissions for air quality analysis purposes, NYSDEC uses forecasts of VMT provided by NYSDOT. These VMT forecasts were created for 13 vehicle categories to match the vehicle categories in the Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) tool. In this study, the VMT from these 13 vehicle categories were aggregated into five stock rollover vehicle categories in the PATHWAYS framework (Light Duty Autos, Light Duty Trucks, Medium Duty Trucks, Heavy Duty Trucks, Buses), and the non-stock category (Transportation Other) for tracking energy demand for all other onroad transport. When calculating VMT forecasts, E3 further aggregated vehicle stock categories into light duty vehicles and all other vehicles. This aggregation is mapped in Table 14.

Table 14. Mapping of EPA MOVES vehicle category to PATHWAYS vehicle category and VMT forecast category

NYSDOT / NYSDEC vehicle category for MOVES analysis	Vehicle category within PATHWAYS	VMT category for E3 VMT forecasting methodology
Passenger Car	Light Duty Autos	Light Duty Vehicle
Passenger Truck	Light Duty Trucks	
Light Commercial Truck	Light Duty Trucks	
Single Unit Long-haul Truck	Medium Duty Trucks	Other
Single Unit Short-haul Truck	Medium Duty Trucks	
Refuse Truck	Medium Duty Trucks	
Combination Short-haul Truck	Heavy Duty Trucks	
Combination Long-haul Truck	Heavy Duty Trucks	
Intercity Bus	Buses	
Transit Bus	Buses	
School Bus	Buses	
Motorcycle	Transportation Other	
Motor Home	Transportation Other	
Source: MOVES vehicle categories from NYSDOT,[13] PATHWAYS vehicle categories defined by E3.		

The NYSDOT provided VMT forecasts, aggregated by E3 into Total VMT, and Light Duty Vehicle (LDV) VMT, are reported in, Table 15,below. As described above, Total VMT includes vehicle travel for all on-road vehicle types simulated within the MOVES tool but does not include non-road vehicles, which are assessed separately.

Table 15. NYSDOT VMT forecast

Year	Total VMT (million miles)	VMT decadal CAGR*	LDV VMT (million miles)	LDV VMT decadal CAGR	Population (million people)	Population decadal CAGR
2020	126,923	N/A	117,684	N/A	20.15	N/A
2030	137,298	0.79%	127,382	0.80%	20.60	0.19%
2040	147,672	0.73%	137,081	0.74%	20.79	0.19%
2050	158,047	0.68%	146,780	0.69%	21.20	0.19%

Note:

*Decadal CAGR = CAGR for previous decade (e.g., 2030 VMT Decadal CAGR = CAGR from 2020-2030).

Sources: VMT growth from NYSDOT,[13] population from E3 forecast based on Cornell population forecast average growth rate.[17]

The national VMT and population forecasts from the 2019 EIA AEO Reference case projection are presented in Table 16 for comparison.

Table 16. EIA AEO 2019 VMT forecast

Year	Total VMT (million miles)	Total VMT decadal CAGR*	LDV VMT (million miles)	LDV VMT decadal CAGR	Population (million people)	Population decadal CAGR
2020	3,364,603	N/A	2,951,370	N/A	333.05	N/A
2030	3,574,223	0.61%	3,107,168	0.52%	355.30	0.65%
2040	3,799,947	0.61%	3,268,648	0.51%	373.53	0.50%
2050	4,073,929	0.70%	3,472,651	0.61%	388.73	0.40%

Note:

*Decadal CAGR = CAGR for previous decade (e.g., 2030 VMT Decadal CAGR = CAGR from 2020-2030).

Source: EIA AEO 2019 Reference case.[40]

As seen in Table 16, the EIA forecasted growth rate for VMT is not identical to EIA forecasted population growth rate. During the time period of the fastest VMT growth rate and slowest population growth rate, in the 2040-2050 decade, the AEO LDV VMT growth rate is 0.61% while the AEO population growth rate is 0.40%; the ratio between these two (LDV VMT CAGR divided by AEO population CAGR) is approximately 1.5. A similar ratio calculated with New York data, comparing the NYSDOT VMT growth rate and the Cornell population growth rate, would result in a ratio of between 3 to 4. This indicates that the implied relationship between the NYSDOT VMT growth estimate and Cornell sourced population growth is much higher than the EIA AEO Reference case VMT growth rate. While the relationship between VMT and underlying growth rates is complex, E3 believes that using the NYSDOT forecast, which has a much higher VMT growth rate than the Cornell population growth rate this study used, would over-estimate VMT demand, especially in the mid-century time frame. Therefore, E3 projected VMT by using the NYSDOT passenger VMT forecasted growth rate through 2030 and forecasted slower growth rate beyond 2030. As discussed above, during the decade of the fastest VMT growth and slowest population growth in the AEO forecast, dividing the VMT growth rate by the population growth rate in AEO gives a factor of 1.5. E3 multiplied the New York population growth rate by this factor to estimate a VMT growth rate beyond 2030 for this study.

Federal Highway Administration analysis on VMT forecasting methods indicate non-LDV VMT growth is more strongly correlated to GDP growth, demand for shipping services, and fuel price forecasts than to population or household growth. [42] Both the EIA AEO and Federal Highway Administration indicate that non-LDV VMT will likely have a higher growth rate than passenger vehicles in future years.[40,42] Since the NYSDOT VMT forecast for the non-LDV vehicle classes also includes a higher growth rate than passenger vehicles, for this study E3 continued to use the NYSDOT VMT growth rates for these non-LDV vehicle classes.[43]

The VMT growth rates used in this study are provided in Table 17. While this table provides a snapshot value every decade, E3 interpolated the CAGR between these decadal years to ensure the growth forecast did not have discontinuities or jumps between simulated years.

Table 17. E3 VMT forecast growth rates

Year	Total VMT (million miles)	Total VMT CAGR	LDV VMT (million miles)	LDV VMT CAGR	Other VMT (million miles)	Other VMT CAGR
2020	126,923	N/A	117,684	N/A	9,239	N/A
2030	137,298	0.79%	127,382	0.80%	9,916	0.71%
2040	141,748	0.32%	131,157	0.29%	10,591	0.66%
2050	146,304	0.32%	135,037	0.29%	11,267	0.62%

Source: E3 calculation based on NYSDOT VMT data,[13] federal VMT and population data from AEO,[40] and population forecast from Cornell.[17]

Table 18 shows a comparison of the CAGR based on the NYSDOT data source and the E3 analysis for 2020-2050; note that Other VMT (primarily freight) has the same growth rate in both datasets, while the LDV VMT growth rate is reduced using the E3 methodology. This lower VMT growth rate results in VMT that is lower by about 5% in 2050 relative to the methodology of growing VMT by the NYSDOT 2017-2050 average VMT growth rate. This is a significant difference, but E3 believes it is a more reasonable estimate of growth as it aligns passenger growth more closely with population growth in this study. Freight growth rates being higher than population growth is reasonable as this relationship is true in the AEO forecast of freight VMT, and analysis put forward by the US Department of Transportation.[40,43]

Table 18. 2020-2050 Average VMT CAGR comparison: NYSDOT vs E3 values

Data Source	Total	LDV	Other (all non-LDV on-road categories)
NYSDOT	0.734%	0.739%	0.664%
E3 Methodology (used in this analysis)	0.475%	0.460%	0.664%

Statewide VMT in forecasted years was calculated by applying a VMT growth rate to the total VMT in each PATHWAYS vehicle category. The VMT for initial simulated year in each PATHWAYS vehicle category can be calculated by multiplying the number of vehicles and the VMT per vehicle for each category, as found in Table 13, with the resulting VMT reported in Table 19. Each of these PATHWAYS vehicle categories was assigned either the LDV or the Other VMT growth rate as calculated in Table 17; the allocation of VMT forecast growth rate by PATHWAYS vehicle category is documented in Table 19 and the resultant statewide VMT is produced in Figure 11. Note this figure aggregates light duty autos and light duty trucks into one vehicle type, light duty vehicles.

Table 19. Initial VMT by PATHWAYS vehicle category and forecasted category

PATHWAYS vehicle category	Initial (2015) VMT statewide (million miles)	VMT forecast growth rate category
Light Duty Autos	49,821	LDV
Light Duty Trucks	64,228	LDV
Medium Duty Trucks	3,513	Other
Heavy Duty Trucks	3,343	Other
Buses	1,042	Other

Source: Initial VMT data from E3 analysis of NYSDOT data.[13]

To calculate VMT for upstate and downstate regions, the distribution of total VMT by road type and county was calculated from the NYSDOT forecast and then applied to the VMT totals that were calculated using E3's recommended growth rates. Table 20 shows the resultant allocation of VMT by county and road type. This allocation preserves the NYSDOT forecast of the regional split between upstate and downstate VMT while using the E3 methodology describe above to calculate total VMT.

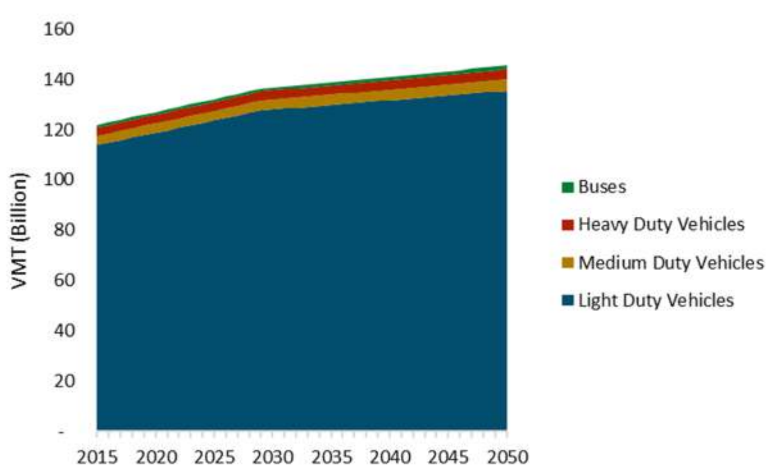
Table 20. Regional allocation of VMT by vehicle category

	LDV VMT regional allocation		Other VMT regional allocation	
Year	Upstate LDV VMT	Downstate LDV VMT	Upstate Other VMT	Downstate Other VMT
2020	46%	54%	55%	45%
2030	46%	54%	54%	46%
2040	45%	55%	54%	46%
2050	44%	56%	53%	47%

Source: NYSDOT through personal communication with NYSERDA.[13]

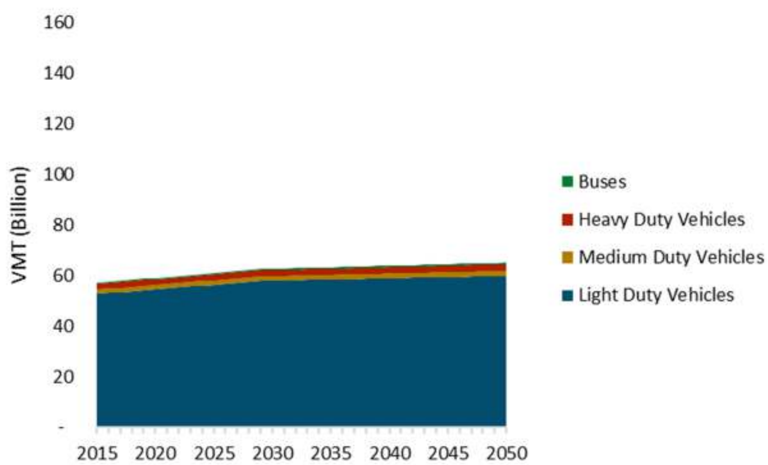
Figure 11, Figure 12, and Figure 13 show the resulting forecasted VMT for the whole state, upstate, and downstate regions, respectively.

Figure 11. New York statewide forecasted VMT by vehicle type



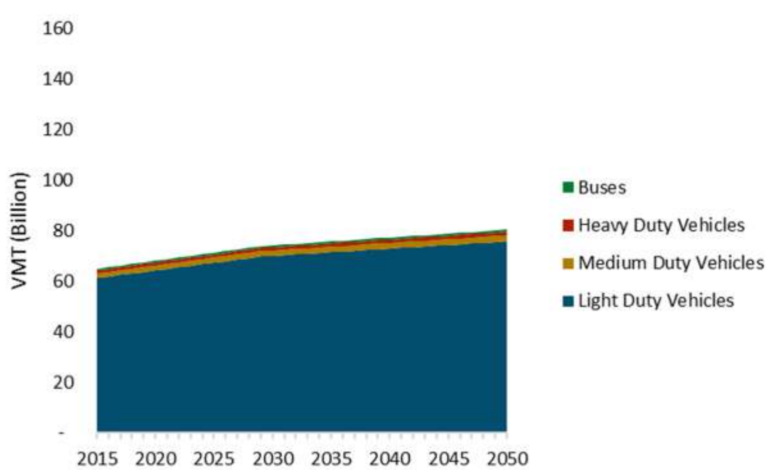
Source: E3 analysis of NYSDOT VMT data,[13] AEO forecast VMT,[40] and Cornell population forecast.[17]

Figure 12. New York upstate region forecasted VMT by vehicle type



Source: E3 analysis of NYSDOT VMT data,[13] AEO forecast VMT,[40] and Cornell population forecast.[17]

Figure 13. New York downstate region forecasted VMT by vehicle type



Source: E3 analysis of NYSDOT VMT data,[13] AEO forecast VMT,[40] and Cornell population forecast.[17]

4.2 Mitigation options

To decarbonize the on-road transportation sector, E3 included a variety of measures including electrification, fuel switching to low-carbon fuels (renewable fuels, hydrogen), and efficiency improvements. In addition, the study included a set of reductions in service demand, in this case in total VMT.

4.2.1 DEMAND REDUCTION, SYSTEM EFFICIENCY, AND PUBLIC TRANSIT

As discussed in other decarbonization reports,[44–49] a potentially cost-effective GHG emissions reduction approach is to reduce energy demand through energy efficiency measures. In the context of transportation, this includes energy efficiency in technology (e.g., more efficient vehicles), and efficiency in reduced demand for transportation. For passenger vehicles, E3 analyzed smart growth strategies[v] to reduce the demand for VMT in personal vehicles.

VMT reductions for passenger, light duty vehicles in New York were calculated as a function of both transportation mode-shifting[vi] and smart growth strategies concerning the built environment. Reductions were calculated for the upstate and downstate regions and then weighted by regional share of total VMT to determine statewide results. The smart growth design principles considered fall into what is commonly referred to as the four Ds: density, diversity, design, and destination accessibility. Density is typically a measure of population or employment density, diversity refers to the diversity of land use in a given area, design measures the street network characteristics within an area, while destination accessibility measures ease of access to destinations (e.g., offices, retail,

[v] Smart growth strategies focus on modifying land-use patterns to reduce the number and length of motor vehicle trips

[vi] Mode-shifting in transportation is switching between different types of transportation, such as moving away from using passenger vehicles towards using mass transit or buses.

schools, etc.) VMT elasticities for the 4Ds were taken from a report on smart land use and VMT reduction, prepared for NYSERDA and NYSDOT, and are show in Table 21.[50]

Table 21. VMT elasticities for smart growth strategies

Smart growth strategy	VMT elasticity
Density	-5%
Diversity	-5%
Design	-4%
Destination Accessibility	-20%
Source: NYSERDA and NYSDOT report on smart land use and VMT reduction.[50]	

To capture regional differences in smart growth potential, E3 assumed that incremental smart growth would occur in counties outside of New York City where population is projected to increase by 2050. The saturation levels of smart growth strategies were determined using targets established in the *Moving Cooler* report published by United States Department of Transportation (DOT) in 2009: these targets include Level A ("Expanded Best Practice") and Level B ("More Aggressive") shown in Table 22.[47] The maximum level of smart growth strategy saturation here is 100%.

Table 22. Smart growth strategy levels in DOT Moving Cooler report

Measure	Level A smart growth	Level B smart growth
Planned Compact Share of Development	60%	70%
Compliance with Compact Development Plans	72%	90%
Baseline Compact Share for Development	34%	34%
Overall Compact Share for Development	43%	63%
Incremental Compact Share for Development	9%	29%
Source: *Moving Cooler* report.[47]		

E3 characterized population increases as occurring in new development within each region, while every decade 10% of the existing region was assumed to undergo redevelopment; this assumption represented the turnover of existing housing stock over time, in line with assumptions made in the *Moving Cooler* analysis.[47] The population and regional new development and redevelopment trends for the selected regions are shown in Table 23.

Table 23. Regional population increases and development

Counties with population increase	Upstate	Downstate (excluding New York City)
2015 population	2,817,460	3,141,633
2050 population	2,940,799	3,504,916
Population in new development areas, 2015-2050	123,339	363,283
Population in redevelopment areas, 2015-2050	986,111	1,099,572
2050 share of population in each region in new or redeveloped areas	37.7%	41.7%
Source: *Moving Cooler* report.[47]		

The incremental share of compact development (see Table 22) was multiplied by the share of population living in new and redeveloped areas (see Table 23) and finally the entire regional population (calculated using regional population growth rates as in Table 2) to determine upstate and downstate saturation levels for smart growth strategies. These saturation levels were assumed to be equal for the 4D's due to the compound benefits of compact development. The saturation levels were then multiplied by the VMT elasticities of the 4D's to determine relative VMT reductions, which are shown with regional saturation levels in Table 24.

Table 24. Smart growth strategy saturation levels and relative VMT reductions in Decarbonization Pathways scenarios.

VMT reduction strategy	Downstate – % Saturation by 2050	Upstate - % Saturation by 2050	Downstate – LDV VMT reductions by 2050	Upstate - – LDV VMT reductions by 2050
Density	2.8%	5.4%	0.14%	0.27%
Diversity	2.8%	5.4%	0.14%	0.27%
Design	2.8%	5.4%	0.11%	0.22%
Destination Accessibility	2.8%	5.4%	0.55%	1.09%
Source: E3 analysis of smart growth and VMT reduction based on NYSERDA, federal, and New York City data sources.[47,48,50–52]				

Two transportation mode-shifting options were also considered in the analysis: mass transit (bus & rail) and walking/biking. Downstate targets for these categories in the Decarbonization Pathways scenarios were partially based on the 2050 goals published by New York City in the *OneNYC* report in 2019.[48] E3 applied a set of assumptions to each category to convert the *OneNYC* goals from share of all trips made into VMT reductions. For personal driving trips shifted to mass transit, E3 used an assumption from the *Moving Cooler* report that 88.2% of transit passenger miles are saved vehicle miles traveled. For the incremental 9% of personal driving trips being shifted to biking (target from the *OneNYC* report), E3 assumed that these trips would be of equal distance to average bike trip distance, which were found to be roughly half of average car trip distance in New York City using data from Citi Bike[51] and a CEOs for Cities report.[52] As a result, E3 assigned a 4.77% decrease in VMT to the 9% of personal driving trips being shifted to biking. Because the *OneNYC* goals do not include any incremental increase in share of trips made by walking, the VMT reductions in the walking & biking category come exclusively from mode-shifting to biking. The New York City VMT reduction impacts for both mode-shifting options are shown in Table 25.

Table 25. New York City VMT reductions for transportation mode-shifting

Mode-shifting option	*OneNYC* Incremental 2050 targets (trip share)	Transit miles / personal vehicle miles	VMT reduction impact
Mass transit (bus & rail)	4.0%	0.88	4.0%
Walking & biking	9.0%	0.53	4.77%

Sources*:*
OneNYC targets from *OneNYC* volume 8 of 9*, "Efficient Mobility"*[48]*, m*ass transit miles per personal vehicle mile from *Moving Cooler,*[47] walking and biking miles per personal vehicle mile from Citi Bike and a CEO for Cities report.[51,52]

For the upstate region and downstate region outside of New York City, targets for trip share were determined based a NYSDOT report on the transportation profile of New York State.[53] The report includes trip data on daily commutes from the 2010 American Community survey for both New York City and the rest of the state. This was assumed to be representative of the breakdown of trip share in the state since non-commute trips were not reported by geographic division. For the upstate region and downstate region outside of New York City, the Decarbonization Pathways scenarios targets were assumed to be a 100% increase in trip share for both transit and walking/biking. The mode-shifting targets are shown in Table 26. These targets are represented as both overall trip share targets, and incremental (relative to 2010) trip share targets.

Table 26. Non-New York City mode-shifting targets.

	Existing (2010)	Decarbonization Pathways scenarios
Overall Trip Share Targets		
Mass Transit (Bus & Rail)	6.2%	12.4%
Walking & Biking	3.8%	7.6%
Incremental Trip Share Targets		
Mass Transit (Bus & Rail)	N/A	6.2%
Walking & Biking	N/A	3.8%

Source: Existing trip share data from NYSDOT,[53] and Decarbonization Pathways scenario targets assumed doubling of trip share for mass transit; walking and biking.[53]

The final mode-shifting saturation level for the downstate was calculated as a population-weighted average using the New York City and non-New York City targets. Mode-shifting saturation levels for both regions are shown in Table 27 below.

Table 27. Saturation levels for mode-shifting strategies.

VMT reduction strategy	Downstate - Decarbonization Pathways scenarios incremental saturation by 2050 (%)	Upstate - Decarbonization Pathways scenarios incremental saturation by 2050 (%)
Mass Transit (Bus & Rail)	4.60%	6.20%
Walking & Biking	8.10%	3.80%
Sources: Upstate saturation levels from E3 analysis of NYSDOT transportation profile data (see Table 26), downstate saturation level is population weighted average of upstate trip share saturation and New York City trip share saturation (see Table 25).		

4.2.2 ENERGY EFFICIENCY AND ELECTRIFICATION

In addition to reducing demand for transportation services as described in the VMT reduction strategies above, another mitigation strategy to reduce emissions associated with transportation is to increase efficiency of vehicles and electrify where possible. Electrified options are feasible today for many vehicle types, an increasing share of which are at or near commercial status. In some use cases, such as some light duty vehicles and intra-city buses, electric vehicles are already near cost-competitive for the consumer and can offer significant complementary benefits such as simpler maintenance and reduced air pollution. Federal grants and NOx mitigation funds from the VW settlement are helping to offset the cost premium for school and transit buses, heavy duty trucks and off-road technologies, hastening their commercialization.

4.2.2.1 Light duty vehicles

Light duty vehicle efficiency for fossil fuel vehicles were sourced from the AEO 2019 Reference scenario, which include improvements in the Corporate Average Fleet

Efficiency (CAFE) standards through vehicular model year 2026.[40] Improved efficiency through CAFE standards are not enough for the state to achieve its climate targets, and so a significant mitigation strategy to decarbonize light duty vehicles is electrification.

A variety of electric light duty vehicle models are commercially available today, and range is increasing with new models, such as the Chevrolet Bolt and Tesla Model 3, able to drive 200 miles or more on a single charge. The price premium of EVs is widely expected to fall as battery technology improves, competition rises, and manufacturing scale improves, with some analysts projecting purchase price parity as soon as the mid-2020s.[54] E3 characterized electric light duty vehicles as having the same annual driving profile as conventional fossil fuel equivalents. The calculation for average miles driven per vehicle is discussed in the VMT forecasting section above (4.1.1). The efficiency of electric vehicles, higher than those of internal combustion engines due to the efficiency benefits of electric powertrains, were sourced from NREL EFS. [41]

E3 also considered the potential impact of light duty vehicle electrification on electric system peak loads. For further details on the methodology used to calculate hourly electric loads for vehicle charging, see Section 7.2.

4.2.2.2 Other onroad electrified transport

This section briefly discusses electrification options for other electrified transport, including buses; on-road freight; and other off-road.

Buses: Electrified transit and shuttle buses have achieved commercial status, with many models available and a favorable total cost of ownership proposition. Intra-city buses represent a small portion of on-road energy use but could be a key early application of electrified vehicle technology. California’s Air Resources Board recently announced a target of 100% of new buses being electric by 2029, with full fleet electrification by 2040.[55]

Inter-city buses, with longer routes and larger bodies, will likely trail other bus applications in being electrified.

Electrified Trucking: Heavy duty trucks are more challenging to electrify than light duty vehicles due to greater energy density needs, particularly long-haul trucks. Heavy duty trucks that are driven intensively on short, fixed routes are the best early category for electrification; this is about 50% of the national heavy-duty fleet.[56] E3 anticipate that hydrogen fuel cell vehicles may be more economic for long-haul trucking than battery-electric vehicles given the energy density required for these trips, since hydrogen is a lighter, more energy-dense fuel than electricity stored in chemical batteries. This class of vehicles and battery technologies are transforming rapidly, so some applications could eventually move toward battery electric technologies. The policies, observed trends, and studies listed in Table 28 offer support for the assumption that some level of MDV/HDV electrification will occur absent additional policy drivers.

Table 28. Freight EV studies, policies, and trends

Category	Details
Study	McKinsey & Company, "What's sparking electric vehicle adoption in the truck industry?" (2017) BEVs could reach 8 to 27 percent sales penetration for MDTs by 2030 in "late adoption" scenario (15 to 34 percent in "early adoption").[57]
Study	UPS/GreenBiz "Curve Ahead: The Future of Commercial Fleet Electrification" (2018) "According to several GreenBiz interviewees, these medium-duty delivery trucks can be deployed today at the same cost as diesel vehicle alternatives.[58]
Study	US DoT/FHWA, "Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses" Pilot study of real electric buses shows Battery Electric Buses lower cost than hybrids and diesels per mile.[59]
Policy	Additional $20 million in funding for New York Truck Voucher Incentive Program (NYTVIP), a diesel truck and bus replacement program.[60]
Policy	NYCHA to replace light-duty and medium-duty trucks with EV trucks where possible and economic.[61]
Trend	UPS to convert up to 66% of NYC fleet to all-electric vehicles.[62]
Trend	Amazon order for 100,000 all-electric delivery vehicles.[63]
Trend	Ikea pledge to electrify all-last mile delivery in NYC by 2020.[64]
Sources: See details column for sources for each study, policy, or trend identified in table.[57–64]	

4.2.2.3 Non-Road Applications:

In aviation, E3 assumed the proposed Federal Aviation Administration "CLEEN 2" policies could reduce jet fuel demand by 10% in 2030 and 40% in 2050, relative to a counterfactual no-efficiency scenario, through engine and operational efficiency improvements.[65]

Electrified vehicles and equipment are increasingly available for airports, seaports, railroad networks and warehouses. Many of these technologies are in the pre-commercial and early commercial stages and are being deployed in regions that are in non-attainment[vii] for air pollutants and/or where there are initiatives to reduce exposure of surrounding communities to diesel emissions.[66] Aviation accounts for much of this demand, with marine and rail making up most of the remainder. Each of these categories pose distinct challenges to electrification, often favoring decarbonized liquid fuels (biofuels and/or hydrogen).

In aviation, weight limits favor energy-dense liquid fuels over batteries. Electrification of short-haul flights may be increasingly appealing as the energy density of batteries continues to improve.[67] However, electrification of long-haul flights will likely require the development of new battery technologies. E3 conservatively assumed no electrification of aviation occurs.

Marine transportation can be divided between marine freight, and recreational and passenger boats. Electrification is more feasible in the latter category, which consists of smaller watercraft and shorter trips. In marine freight, E3 assumed approximately 20% of fuel use can be cost effectively electrified with current technologies, corresponding to energy use in port operations and by ships hoteling, or operating while docked.[68] The world's largest shipping company has set a technology-agnostic goal of reducing carbon

[vii] An area is in non-attainment if the U.S. EPA formally designates the area does not meet air quality standards for one or more specific pollutants the EPA considers "criteria pollutants", which are indicators of air quality

emission to zero by 2050, suggesting that the decarbonization of maritime freight is an important avenue for technological development.[69]

Finally, opportunities remain to electrify diesel passenger rail and certain segments of freight networks. Electrification is likely to be expensive over longer lengths of the rail network, suggesting that electrification alone is not a feasible mitigation strategy for rail transport.[70] This analysis assumed that 20% of the diesel demand for rail could be electrified in the Decarbonization Pathways scenarios, with the remaining demand could met with decarbonized fuel such as renewable diesel or hydrogen.

4.2.3 HYDROGEN AND ADVANCED BIOFUELS

Advanced Biofuels: Advanced drop-in biofuels play a key role in mitigating some emissions from the remaining hard-to-electrify end uses, particularly aviation and freight. However, the availability of drop-in biofuels is limited due to the limited feedstock of sustainable biomass which can be used to produce biofuels. In this study advanced biofuels in transportation were targeted for end uses which have limited other decarbonization options, specifically for aviation; highway freight; and marine uses. For more details on the biomass feedstock assumptions and the efficiency of the processes used to convert biomass feedstock to advanced drop-in biofuels, see Section 6.1.

Hydrogen: The combination of high efficiency and high energy density makes hydrogen fuel cells an appealing technology for decarbonizing the transportation categories that are most difficult to electrify. Hydrogen fuel cells provide an efficient electric drivetrain and superior energy density to batteries, but hydrogen fuel is more expensive than electricity due to the need to produce hydrogen from zero emissions electricity, as well as transport it. In this study, electrolysis was assumed to be the hydrogen production technology, in which hydrogen gas can be produced from water and electricity to produce hydrogen gas; liquefaction can subsequently be used to produce liquid hydrogen, which is easier to transport and store than hydrogen gas and can be used as a decarbonization option within transportation applications. This step requires additional electricity and the incremental capital expense of liquefaction plants.[71]

5 Industry

5.1 Analysis approach

This section describes the methodology for calculating energy demand within the industrial sector, the approach to segmenting statewide industrial energy demand by subsector and fuel, and the geographic allocation of industrial energy demand to the upstate and downstate regions. Note this section focuses on energy demand within industry; non-combustion emissions related to industrial processes are covered in Section 2.4.

E3 used a total energy approach to characterize the industrial subsectors. E3 benchmarked simulated energy demand in the industry sector to statewide industrial energy demand by fuel, obtained from NYSERDA's *Patterns and Trends* report published in January, 2019.[11] The *Patterns and Trend* report includes fuel consumption data for industry obtained from SEDS.[28] SEDS uses a variety of survey data to estimate statewide and nationwide energy consumption by sector. SEDS defines the industrial sector as all facilities and equipment used for producing, processing, or assembling goods, and considers the industrial sector to encompass manufacturing; agriculture, forestry, fishing, hunting; mining, including oil and gas extraction; and construction. The *Patterns and Trends* report includes the energy demand for transporting natural gas in the "Transportation" sector, while E3 analyzed the energy demand for transporting natural gas in the industrial sector in this study.

E3 disaggregated industrial energy consumption by subsector to differentiate electrification potential by subsector. The NYSERDA *Energy Efficiency and Renewable Energy Potential Study of New York State*[26] (*Energy Efficiency Potential Study*) segments energy demand for electricity, natural gas, and petroleum among different industrial subsectors, with further granularity in segmenting energy use among manufacturing subsectors. The industrial subsectors identified in the *Energy Efficiency Potential Study* include agriculture, mining, construction, and manufacturing; these are the subsectors which E3 segments industrial energy demand into as well.

To calculate energy demand for the first simulated year, E3 scaled fuel consumption data from the *Energy Efficiency Potential Study* to match industry sector fuel demand from the *Patterns and Trends* report, while also incorporating fuel demand for transporting natural gas into the industrial sector profile in this analysis. Since the fuel consumption data from the *Energy Efficiency Potential Study* data are from 2013 and report lower fuel consumption than the data found in the *Patterns and Trends* report, E3 scaled the energy demand from the subsectors in the *Energy Efficiency Potential Study* data to benchmark to industry sector fuel consumption from the *Patterns and Trends* report. In this way, E3 captured data on the distribution of fuel demand between industrial subsectors from the *Energy Efficiency Potential Study*, while benchmarking total industrial fuel demand to the more recent *Patterns and Trends* report. Table 29 is a snapshot of industrial energy consumption from the *Energy Efficiency Potential Study*, which informed the estimate of fuel use by industrial subsector.

Table 29. Industrial fuel demand by subsector, 2013

	Electricity (GWh)	Electricity (%)	Natural Gas (BBtu)	Natural Gas (%)	Petroleum (BBtu)	Petroleum (%)
Agriculture	116	0.8%	461	0.5%	928	3.4%
Mining	27	0.2%	141	0.1%	56	0.2%
Construction	766	5.0%	8,314	8.2%	18,439	67.9%
Total Manufacturing	14,329	94.0%	92,085	91.2%	7,824	28.8%
Food	*414*	*2.7%*	*3,794*	*3.8%*	*37*	*0.1%*
Paper	*363*	*2.4%*	*2,128*	*2.1%*	*213*	*0.8%*
Chemical	*6,093*	*40.0%*	*62,190*	*61.6%*	*2,579*	*9.5%*
Plastics & rubber products	*629*	*4.1%*	*1,496*	*1.5%*	*45*	*0.2%*
Nonmetallic mineral products	*1,220*	*8.0%*	*5,565*	*5.5%*	*2,704*	*10.0%*
Primary metal	*3,264*	*21.4%*	*6,653*	*6.6%*	*1,158*	*4.3%*
Fabricated metal product	*363*	*2.4%*	*1,782*	*1.8%*	*29*	*0.1%*
All other	*1,983*	*13.0%*	*8,376*	*8.3%*	*1,059*	*3.9%*
Total Industrial Sector	**15,239**	**100%**	**101,000**	**100.0%**	**27,156**	**100%**

Source: *Energy Efficiency Potential Study, Volume 2.*[13]

Table 31 is a snapshot of the estimated industrial fuel usage by subsector and fuel in this study. This was informed by both the *Energy Efficiency Potential Study* data, reported in Table 29, and *Patterns and Trends* data on fuel use by industry in 2015.[11]

Table 30. Industrial fuel demand by subsector, state-wide 2015

Subsector	Electricity (TBtu)	Natural Gas (TBtu)	Other (TBtu)
Agriculture	0	1	2
Mining	0	0	0
Construction	3	10	47
Manufacturing Subsectors:	58	111	20
Food	*2*	*5*	*0*
Paper	*1*	*3*	*1*
Chemical	*25*	*75*	*7*
Plastics	*3*	*2*	*0*
Cement	*4*	*1*	*5*
Other Minerals	*1*	*6*	*1*
Aluminum	*13*	*8*	*3*
Fabricated Metals	*1*	*2*	*0*
Other	*8*	*10*	*3*
Total Industrial Sector	**61**	**122**	**69**

Source: E3 estimate of industrial fuel demand by subsector from scaling *Energy Efficiency Potential Study*[26] data on fuel use by subsector and fuel in 2013 to *Patterns and Trends*[11] data on fuel use by sector for 2015.

To allocate industrial energy demand to the upstate and downstate regions in this study, E3 used a different geographic allocation for each industrial sector (agriculture, mining, construction, manufacturing); the geographic allocation of industrial energy demand for each industrial subsector is described in Table 31.

Table 31. Geographic allocation of industrial energy demand

	Energy consumed upstate (%)	Energy consumed downstate (%)	Methodology for allocation
Agriculture and Mining	100%	0%	For Agriculture and Mining subsectors, E3 assumed that all energy demand is upstate. A small amount of fuel consumption associated with agricultural activity on Long Island is therefore included in the upstate estimates.
Construction	26%	74%	E3 used 2017 data from the US Bureau of Labor Statistics (BLS).[72] BLS provides data for construction jobs at the state level, as well as regional data for the larger category of jobs in "Construction, Mining, and Logging." E3 assumed that the number of mining and logging jobs downstate is insignificant and thus these numbers reflect downstate construction jobs. Upstate jobs are then computed as the difference between statewide and downstate.
Manufacturing Subsectors	90%	10%	In this study the upstate/downstate geographic allocation is most important for capturing upstate/downstate constraints between NYISO zones. *Patterns and Trends* Appendix F-3 indicates that 90% of industrial electricity use occurs upstate. Therefore, for all manufacturing subsectors E3 allocated 90% of energy demand to the upstate region. While the geographic allocation of other fuels, such as natural gas, may not correspond with the geographic allocation of electricity use, in this study the geographic allocation is most important for capturing geographic differences in load, and thus using the geographic allocation of electricity demand as a proxy for the rest of industrial fuel demand was used.
Sources: E3 analysis of Bureau of Labor Statistics data on construction, mining, and logging jobs[72] and *Patterns and Trends* data on industrial electricity use.[11]			

To forecast industrial energy demand, E3 forecasted the growth of industrial energy demand for each industrial subsector. These subsectoral growth rates are obtained from a variety of sources and are summarized in Table 32.

Table 32. Assumed growth rates for industry subsector energy demand forecast

	CAGR 2017-2050	Data source
Agriculture	United States population growth rate 2017-2050	EIA AEO 2019
Mining	United States population growth rate 2017-2050	EIA AEO 2019
Construction	New York State population growth rate 2017-2050	Cornell population forecast
Manufacturing Subsectors:	0.6% (proxy for manufacturing related economic growth calculated by downscaling AEO US GDP growth by ratio of population growth rate for NYS/US)	EIA AEO 2019
Sources: US population growth rate obtained from EIA AEO 2019,[10] New York State population growth rate sourced from Cornell population forecast.[17]		

5.2 Mitigation options

There are relatively few public data sources on energy consumption and devices within the industrial sector. The industrial sector is highly diverse, and firms have optimized complex processes to take advantage of historically inexpensive fossil fuel energy sources. Nevertheless, there are cost-effective energy efficiency opportunities within many industrial subsectors. Furthermore, some industrial subsectors electrification can offer process improvement, such as for electric arc furnaces or in using heat pumps for industrial heating, ventilation, and air conditioning (HVAC); in other areas electricity can displace higher cost fossil alternatives such as liquid petroleum fuels. Thus, E3 included significant efficiency and electrification measures to reduce fossil fuel usage in the Decarbonization Pathways scenarios. In some applications, such as high-temperature applications or in processes optimized around pipeline gas, electrification might not be a viable strategy. For these applications, mitigation options include switching to lower carbon fossil alternatives (e.g., switching coal and coke to natural gas); switching to low-carbon biofuels or synthetic fuels; as well as some amount of carbon capture and sequestration.

5.2.1 ENERGY EFFICIENCY

E3 assumed the Reference scenario achieved a 20% reduction in energy demand relative to a counterfactual no-efficiency scenario by 2050, while the Decarbonization Pathways scenarios achieved 30% reduction in energy demand. In the Reference and Decarbonization Pathways scenarios a 10% reduction was assumed to be achieved by 2030. These efficiency improvements were applied across all fuels.

As a comparison, this document also reports the economic and achievable efficiency potential by fuel as reported in the *Energy Efficiency Potential Study* in 2014.[26] The Reference case reduction of 10% by 2030 in this study is comparable to the achievable potential as identified in the *Energy Efficiency Potential Study*. The Decarbonization Pathways scenarios reduction of 30% by 2050 is comparable to the economic potential of energy efficiency as identified in the *Energy Efficiency Potential Study* and as shown in Table 33.

Table 33. Economic and achievable industry EE

	Electricity (GWh)	Natural Gas (BBtu)	Petroleum (BBtu)	All Fuels (BBtu)
2013 Energy Use	15.2	101	27.1	180
Economic Potential by 2030 (% of 2013)	4.7 **(31%)**	35.7 **(35%)**	2.6 **(9.5%)**	54 **(30%)**
Achievable Potential by 2030 (% of 2013)	1.5 **(9.8%)**	11.4 **(11.2%)**	1.3 **(4.7%)**	17.8 **(10%)**
Source: NYSERDA *Energy Efficient Potential Study* 2014.[26]				

5.2.2 INDUSTRY ELECTRIFICATION

Because the chemicals subsector constitutes most of the fuel demand for manufacturing statewide, E3 assumed that potential electrification for chemicals was broadly representative of electrification potential within manufacturing overall. Fuel consumption by end-use was estimated as a fraction of each source based on the fractions provided in EIA's 2014 *Manufacturing Energy Consumption Survey*[73] (MECS).

Industrial electrification potential was forecasted for end uses determined to be electrifiable in National Renewable Energy Laboratory's (NREL) *Electrification Futures Study.*[41] The five end-uses considered in the *Electrification Futures Study* are curing, drying, other process heat, boilers, and space heating. Curing refers to process heating for wood products and drying refers to process heating for plastic and rubber products. Based on energy usage as specified in *Energy Efficiency Potential Study,* E3 believes curing and drying are industrial end-uses which do not exist in great quantities in New York state, so these end-uses were not included in the estimation of industrial electrification potential. The remaining three end-uses from *Electrification Futures Study* were correlated with the three reported end-use categories in MECS as shown in Table 34. Fuel consumption in the "End Use Not Reported" MECS category was not considered electrifiable.

Table 34. Fuel consumption end-use categories considered for electrification.

Electrification Futures Study **category**	**Corresponding *Manufacturing Energy Consumption Survey* category**	**Service demand included in *Manufacturing Energy Consumption Survey* category**
Boilers	Indirect Uses – Boiler Fuel	Conventional Boiler Use, Combined Heat and Power, and/or Cogeneration Process
Other Process Heat	Direct Uses – Total Process	Process Heating, Process Cooling and Refrigeration, Machine Drive, Electro-Chemical Processes, Other Process Use
Space Heating	Direct Uses – Total Non-process	Facility HVAC; Facility Lighting; Other Facility Support; Onsite Transportation; Other Non-process Use
Sources: *Electrification Futures Study*[41] and *Manufacturing Energy Consumption Survey.*[73]		

Table 35 displays the electrification shares for 2015 and the forecasted electrification potential in 2050 in the Reference and Decarbonization Pathways scenarios. These electrification shares were adapted from the *Electrification Futures Study*, and a report on building and industry electrification published by Lawrence Berkeley National Laboratory (LBNL).[74] For the Decarbonization Pathways scenarios, the increased target for Indirect Uses – Boiler Fuel represents the complete electrification of boilers. The remaining unelectrified energy is used as part of combined heat and power and/or cogeneration, end-uses that both NREL and LBNL consider among the least likely candidates for electrification. Finally, the Direct Uses – Total Process target in the Decarbonization Pathways scenarios was increased to 95% to represent nearly complete electrification of these end-uses. The potential for incremental electrification of fossil fuel consumption in the manufacturing subsector was 58% by 2050 in the Decarbonization Pathways scenarios. As natural gas is the most dominant non-electric fuel consumed in manufacturing (Table 30), the potential for incremental electrification of fossil fuel consumption was applied to natural gas; Table 36 displays the incremental among of natural gas which could be electrified in the Reference and Decarbonization Pathways scenarios.

Table 35. Electrification share of net energy consumption by end-use for manufacturing sector

End-Uses	2015	2050 Reference	2050 Decarbonization Pathways
Indirect Uses – Boiler Fuel	1%	1%	29%
Direct Uses – Total Process	38%	38%	95%
Direct Uses – Total Non-process	52%	52%	95%
End-Use Not Reported	12%	12%	12%
Total Sector Electrification	**23%**	**23%**	**66%**
Incremental Electrification	**-**	**0%**	**58%**

Source: 2015 electrification share from E3 analysis of *Manufacturing Energy Consumption Survey,*[73] while 2050 Reference maintains the 2015 share and 2050 Decarbonization Pathways analysis from E3 analysis of New York industrial manufacturing electrification potential based on *Electrification Futures Study*[41] and LBNL report on building and industry electrification.[74]

Table 36. Incremental industry electrification levels analyzed

Scenario	2030	2050
Reference	0%	0%
Decarbonization Pathways	0%	60% remaining* natural gas electrified

Note:

*Remaining natural gas is natural gas after energy efficiency measures reduced natural gas demand

Source: As documented in Table 35, Reference scenario includes no incremental industrial electrification measures while Decarbonization Pathways share of incremental electrification are based on E3 analysis of New York industrial manufacturing electrification potential based on *Electrification Futures Study*[41] and *Electrification of buildings and industry.*[74]

5.2.3 INDUSTRY CCS

As documented in Section 2.6.2.1, the Decarbonization Pathways scenarios included industry CCS as a mitigation option with a potential of capturing and storing up to 1.92 MMT CO_2/year.

6 Low-carbon fuels

Low-carbon fuels play a role in a variety of applications in a deeply decarbonized economy. In this analysis low-carbon fuels are used as drop-in fuels for some types of energy demands which may not be good candidates for electrification, such as aviation or high temperature industrial applications; provide valuable services for electric system reliability when burned in electrical generating units; and are used in areas where electrification might be technically feasible but economically impractical, such as for long distance heavy duty freight trucking. E3 analyzed two types of low-carbon fuels: biofuels, and hydrogen. The previous sections described the use of biofuels and hydrogen in various sectors throughout the economy. This section addresses the production of biofuels and hydrogen; it includes a discussion of the constraints analyzed for the conversion of biomass to biofuel and includes the electricity supply implications of creating hydrogen via electrolysis.

6.1 Conventional biofuels and advanced renewable biofuels

6.1.1 DEFINITIONS AND CURRENT USE IN NEW YORK STATE

In this study biofuels are defined as fuels derived from biomass. Biomass products used as raw materials for producing fuels are called biomass feedstocks. If biomass feedstocks are produced, harvested, transported, and processed without causing adverse environmental impacts, E3 considers the resulting biofuel products as having no lifecycle GHG emissions. In screening potential biomass feedstocks for those with no adverse environmental impacts, E3 relied on a US Department of Energy report on biomass availability within the United States, the *2016 Billion-Ton Report;* this report provides county level estimates of potential biomass production which would cause no adverse environmental impacts.[25]

While the CLCPA requires inclusion of upstream emissions for fossil fuels and states that biofuels are not eligible for carbon offset credits, it is unclear if biofuel emissions accounting would account for biofuels as net zero emission fuels within the CLCPA framework. For this study E3 considers biofuels as having no lifecycle GHG emissions, but future analysis will align biofuels emissions accounting with appropriate CLCPA accounting framework.

Currently in New York, biofuels are used in several forms. Ethanol, produced primarily from U.S. corn, is blended into gasoline at volumes close to 10% to comply with the federal renewable fuel standard.[75] In 2017 Governor Cuomo signed Senate Bill S5422A, which mandated heating oil used in the Nassau, Suffolk, and Westchester counties has at least a 5% biodiesel blending requirement, effective June 2018; this is in addition to already mandated New York City rules mandating heating oil sold in the city to be at least a 5% biodiesel blend, raising to a 20% blend by 2034.[76] Wood and wood pellets are used as heating fuel in buildings,[11] while other forms of woody waste are directly combusted to produce renewable electricity. In aggregate, based on *Patterns and Trends* energy consumption data on wood and waste consumption in New York State, E3 estimates that the current use of biomass in New York State is close to 12 million dry tons of biomass feedstock. A dry ton, also called a bone-dry ton (BDT), is 2,000 pounds of biomass feedstock dried to a moisture content of 0%.

Examples of biomass products that can be used to produce gaseous and liquid biofuels include but are not limited to corn, soybeans, sugar cane, forest products and wood, manure, switch grass and other agricultural waste products, such as corn stover, as well as waste streams such as landfill and wastewater gas; more details on the feedstocks used to produce biofuel in this analysis can be found in 6.1.3.

Advanced biofuels, also known as renewable biofuels, are a type of biofuels that are chemically similar to their fossil counterparts and are therefore 'drop-in' fuels, which can be used as replacement for their fossil counterparts without any modification of the combustion system. E3 considers four categories of advanced renewable biofuels: renewable diesel, renewable jet kerosene, renewable natural gas, and renewable gasoline.

+ **Renewable diesel:** Renewable diesel is a drop-in replacement fuel for fossil diesel; unlike biodiesel, renewable diesel has a chemical composition almost identical to fossil diesel. Currently, biodiesel derived from animal fats, vegetable oils, and waste cooking oils is used as a niche heating fuel. New York City requires that diesel-based heating oil sold in New York City reach a 20% biodiesel blend by 2035.[48] However, there is no statewide blend mandate and biodiesel produced for heating fuel is not suitable for use in transportation without modifications to either the fuel or the engines. Renewable diesel, however, can be used by diesel vehicles of any type (light-duty diesel vehicles, medium- and heavy-duty trucks, off-road equipment, diesel boats, etc.), industrial end uses that rely on diesel, and building heating equipment that use diesel. Biomass products that can produce renewable diesel include a variety of agriculture waste products, forests, and other waste streams. The set of feedstocks and conversion pathways used in this analysis are discussed in 6.1.3.
+ **Renewable jet kerosene:** Renewable jet kerosene is a drop-in replacement fuel for fossil jet kerosene. As is true for renewable diesel, biomass products that can produce renewable jet kerosene include a variety of agriculture waste products, forests, and other waste streams. The set of feedstocks and conversion pathways used in this analysis are discussed in 6.1.3.
+ **Biogas or renewable natural gas:** Biogas or renewable natural gas, upgraded to pipeline grade biomethane, can be used as a drop-in fuel anywhere that natural gas is used in buildings and industry, it can be compressed for use by cars or trucks designed to use compressed natural gas, or can be directly combusted for electricity generation or use in building energy systems. Almost all biomass

products can be used to produce renewable natural gas; the set of feedstocks and conversion pathways used in this analysis are discussed in 6.1.3.

- **Renewable gasoline**: Renewable gasoline is a drop-in replacement fuel for fossil gasoline; unlike ethanol, renewable gasoline has a chemical composition almost identical to fossil gasoline. As is true for renewable diesel, biomass products that can produce renewable gasoline include a variety of agriculture waste products, forests, and other waste streams. The set of feedstocks and conversion pathways used in this analysis are discussed in 6.1.3. Currently, biofuel use in gasoline comes in the form of ethanol blended into gasoline as a fossil gasoline substitute. Ethanol is commonly blended in most gasoline sold with blends up to 10% and may increase up to 15% in some cases in the future. However, unlike renewable gasoline, specialized engines are needed to combust higher concentrations of ethanol. Currently, the most common feedstocks used to produce ethanol are starch- or sugar-based food crops such as corn, sugarcane, or sugar beets.

6.1.2 ANALYSIS APPROACH

To calculate an optimal portfolio of biofuels, E3 has developed a model which generates estimates of biofuel availability and cost. The model optimizes for the selection of a least-cost portfolio of feedstocks and conversion processes given fuel demand, available feedstock, and conversion process. A conversion process is a set of processing steps which convert a feedstock, or set of feedstocks, to a particular biofuel (for instance, pyrolysis or Fischer Tropsch for conversion of wood to diesel[viii]).

E3 used the biofuels optimization model to produce lowest-cost biofuels portfolios which met pre-defined demand for renewable jet kerosene, renewable diesel, and renewable natural gas; the model also produced a wholesale market clearing price for each type of biofuel. The pre-defined demand for biofuels was the result of a manual economy-wide

[viii] Pyrolysis is the process of decomposing materials at high temperature in an inert atmosphere.
Fischer Tropsch is a chemical process which converts carbon monoxide and hydrogen into hydrocarbons.

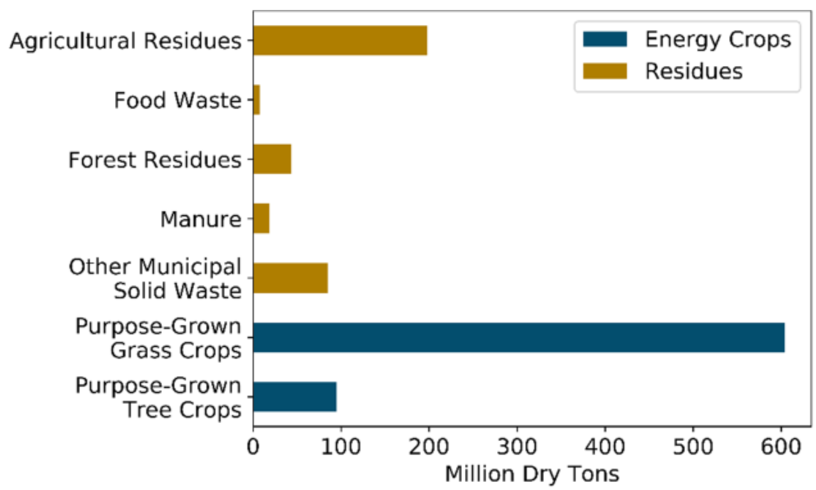
scenario creation process in which biofuels were prioritized for use in sectors which are otherwise difficult to electrify. This was done to ensure this study does not rely on overly optimistic assumptions about biofuel availability and rely on biofuels as the sole option for reducing GHG emissions across the economy.

6.1.3 DATA INPUTS AND BIOMASS CHARACTERIZATION

The first consideration for biofuel production is the availability of sustainable biomass feedstocks. E3 relied on the federal *2016 Billion-Ton Report*[25] as a starting point for county-level projections of biomass supply for the United States. Additional study by New York researchers added additional purpose-grown grasses and timberland to the available in-state biomass feedstock supply.[26]

The *2016 Billion-Ton Report* estimates biomass resource potential across the continental United States based on current and future biomass inventory, production capacity, availability, technology, and sustainability: the study estimates only sustainable biomass potential by excluding from consideration biofuels that would directly compete with food crops, and considers only biomass feedstock whose production would not cause adverse environmental impacts. Biomass feedstock supply and price estimates vary by U.S. county and feedstock type. The *2016 Billion-Ton Report* projects a range of different biomass yield growth scenarios; for this study, E3 used the base case biomass yield growth scenario ("Basecase, all energy crops"). The *2016 Billion-Ton Report* also projects a range of alternative biomass demand, with higher demand reducing the availability of biomass feedstock for conversion to biofuels. For this study, E3 used the "Medium housing, low energy demand" alternative demand for biomass scenario when calculating the county level biomass feedstock available for biofuel production. As seen in Figure 14, most of the national resource is new purpose-grown crops and forests. E3 excluded these purpose-grown crops and forests due to concerns about the land use related GHG emissions associated with purpose-grown crops and forests as opposed to residues and wastes. This exclusion left 352 million dry tons of residue and waste biomass potential nationwide. As noted above, additional study by New York researchers led E3 to include some purpose-grown grasses and timberland into the available in-state supply. The *2016 Billion-Ton Report* groups resources into price bins in $10/BDT increments from $0-10/BDT through $90-100/BDT with an additional $100-1,000/BDT price bin.

Figure 14. Projected national feedstock supply in 2040-2050



Source: Data from *2016 Billion-Ton Report* with "Basecase, all energy crops" case for biomass yield growth and "Medium housing, low energy demand" case for alternative biomass demand.[25]

E3 updated the feedstock screening to exclude non-renewable plastics and other municipal solid waste (MSW). The *2016 Billion-Ton Report* includes some resources derived from petroleum, such as plastics, in the feedstock supply that are shown as available for biofuel production. E3 excluded these resources from eligibility for biofuel production in this study around concerns over their lifecycle GHG impacts.

E3 produced two scenarios of biofuel feedstock availability: an in-state scenario and a regional scenario. The in-state scenario is limited to feedstocks within New York state, while the regional scenario expands the available feedstocks to New York's population weighted share of the available non-farmed biomass. The full list of included and excluded resources in these two scenarios is included in Table 37.

For simplification, E3 grouped feedstocks into four conversion categories: cellulosic, woody cellulosic, lipid, and manure. These feedstock categories share key characteristics that impact conversion processes and costs. Though it is uncertain which sectors and end uses will be best suited to switching from fossil fuels to biofuels, the analysis assumed that the quantities of available biofuels would be limited based on the above feedstock limitations and therefore priority for biofuel use was given to applications which would be difficult to electrify. Specific assumptions and analysis options are discussed below.

- **Renewable diesel:** In this analysis, renewable diesel was used mainly in medium-duty trucks, heavy-duty trucks, and marine vessels.
- **Renewable jet kerosene:** In this analysis, renewable jet kerosene was used in airplanes.
- **Biogas or renewable natural gas:** While there are many potential uses for renewable natural gas, this analysis assumed that biomethane would be blended into the existing natural gas distribution pipeline, thereby displacing fossil natural gas used in building end uses, industrial processes, and as an input into electricity generation.
- **Renewable gasoline**: While it is possible to produce ethanol from waste-product cellulosic feedstocks, this analysis assumed that cellulosic feedstocks would be prioritized to produce other, high-value biofuels. Since the most common feedstocks used to produce conventional ethanol are food crops, in this analysis conventional ethanol use in New York was assumed not to increase due to concerns about relying on food-based biofuels to produce GHG emissions reductions.

Gaseous biofuel conversion assumptions for biomethane production were based on a draft report for the California Energy Commission on the future of natural gas distribution in California.[77] For each feedstock in the *2016 Billion-Ton Report* dataset, and for every 5 years from 2015 to 2050, the study authors determined a single set of parameters to characterize each feedstock and conversion process combination. These factors consist of overall energy efficiency ($GJ_{(HHV)}$[ix]/dry ton) and levelized process conversion costs (2012$/GJ). For further details regarding the gaseous biofuel conversion pathways assumptions, see Table 38. Biofuel demand in the Decarbonization Pathways scenarios is highest in 2050 and that is the year the CLCPA mandates carbon neutrality target economywide, so this table reports the biofuel conversion process assumptions for 2050.

Liquid biofuel conversion pathway assumptions were based on an internal analysis performed by Black and Veatch for E3 in 2016;[78] these conversion pathway assumptions included increases in conversion efficiency over time associated with innovation. As noted above, the demand for biofuels is greatest in the Decarbonization Pathways scenarios when there is the most stringent economywide emissions policy target; since the CLCPA carbon neutrality target is set for 2050, the biofuel conversion process assumptions for 2050 are included in Table 39.

Where multiple conversion processes exist for a given feedstock and final fuel combination, a prescreening step was used to determine the cheapest conversion process. To ensure the cheapest conversion process did not ignore the increased carbon benefit of displacing liquid fossil fuels, the prescreening step included a carbon price of $500/tonne in considering the benefits of increased yield. For instance, hydrolysis of cellulose to produce renewable drop-in gasoline would be preferred to pyrolysis in the 2050 time frame. Pyrolysis would produce biogas, and renewable gasoline is more valuable than biogas both because renewable gasoline has a higher market price than biogas, but also because renewable gasoline displaces more GHG emissions per unit

[ix] HHV: Higher Heating Value. The amount of heat energy available to be released by the combustion of a fuel, including the heat content of the energy used to vaporize water created during the combustion process. Also known as gross heating value.

energy than biogas does. By including a carbon price as a pre-screening step, the biofuels module would value the increased GHG mitigation value of renewable gasoline more than a case where the renewable fuels were compared based solely on energy value. For further details about the liquid biofuel conversion pathways, see Table 39.

Table 37. Biomass resource screening

Resource type	Feedstock (*2016 Billion-Ton Report)*	E3 conversion category	In-state resource screen	Out-of-state resource screen
Agricultural Residues	Barley straw	Cellulosic	Include	Include
	Corn stover		Include	Include
	Oats straw		Include	Include
	Sorghum stubble		Include	Include
	Wheat straw		Include	Include
	Citrus residues	Woody Cellulosic	Include	Include
	Cotton gin trash	Cellulosic	Include	Include
	Cotton residue	Cellulosic	Include	Include
	Non-citrus residues	Woody Cellulosic	Include	Include
	Rice hulls	Cellulosic	Include	Include
	Rice straw	Cellulosic	Include	Include
	Sugarcane bagasse	Cellulosic	Include	Include
	Sugarcane trash	Cellulosic	Include	Include
	Tree nut residues	Woody Cellulosic	Include	Include
Energy Crops	Biomass sorghum	Cellulosic	Include	Exclude
	Energy cane		Include	Exclude
	Eucalyptus		Exclude	Exclude
	Miscanthus		Include	Exclude
	Pine		Exclude	Exclude
	Poplar		Exclude	Exclude
	Switchgrass		Include	Exclude
	Willow		Exclude	Exclude
Food Waste	Food waste	Municipal Solid Waste	Include	Include
Forest Residues	Hardwood, lowland, residue	Woody Cellulosic	Include	Include
	Hardwood, upland, residue		Include	Include
	Mixed wood, residue		Include	Include
	Other forest residue		Include	Include
	Other forest thinnings		Include	Include
	Primary mill residue		Include	Include
	Secondary mill residue		Include	Include

	Softwood, natural, residue		Include	Include
	Softwood, planted, residue		Include	Include
Manure	Hogs, 1000+ head	Manure	Include	Include
	Milk cows, 500+ head		Include	Include
Municipal Solid Waste	CD waste	Municipal Solid Waste	Include	Include
	MSW wood		Include	Include
	Other		Include	Include
	Paper and paperboard		Include	Include
	Plastics		Exclude	Exclude
	Rubber and leather		Exclude	Exclude
	Textiles		Exclude	Exclude
	Yard trimmings		Include	Include
Forest Trees	Hardwood, lowland, tree	Woody Cellulosic	Include	Exclude
	Hardwood, upland, tree		Include	Exclude
	Mixed wood, tree		Include	Exclude
	Softwood, natural, tree		Include	Exclude
	Softwood, planted, tree		Include	Exclude

Table 38. 2050 Biomethane conversion inputs

Feedstock Type (BTS2016)	E3 Feedstock Category (Aggregated)*	Conversion Process[x]	Efficiency (GJ/dry ton)	Process Costs (2012$/dry ton)
Barley straw	Cellulosic	gasification	14.00	80.65
Biomass sorghum	Cellulosic	gasification	13.86	79.28
CD waste	MSW (Wood)	gasification	13.98	80.59
Citrus residues	Woody Cellulosic	gasification	13.74	79.21
Corn stover	Cellulosic	gasification	13.53	78.10
Cotton gin trash	Cellulosic	gasification	14.88	85.97
Cotton residue	Cellulosic	gasification	13.19	76.53
Energy cane	Cellulosic	gasification	13.62	78.26
Eucalyptus	Cellulosic	gasification	15.14	87.15
Food waste	MSW	gasification	11.48	66.41
Hardwood, lowland, residue	Woody Cellulosic	gasification	14.70	84.63
Hardwood, lowland, tree	Woody Cellulosic	gasification	14.70	84.63
Hardwood, upland, residue	Woody Cellulosic	gasification	14.70	84.63
Hardwood, upland, tree	Woody Cellulosic	gasification	14.70	84.63
Hogs, 1000+ head	Manure	anaerobic digestion	7.41	79.81
MSW wood	MSW (Wood)	gasification	14.34	82.76
Milk cows, 500+ head	Manure	anaerobic digestion	8.09	87.13
Miscanthus	Cellulosic	gasification	14.34	82.41
Mixed wood, residue	Woody Cellulosic	gasification	14.70	84.63
Mixed wood, tree	Woody Cellulosic	gasification	14.70	84.63
Non-citrus residues	Woody Cellulosic	gasification	13.65	77.95
Oats straw	Cellulosic	gasification	13.66	78.25
Other	MSW	gasification	12.85	73.55
Other forest residue	Woody Cellulosic	gasification	13.65	77.95

[x] Gasification is conversion of biomass to carbon monoxide, hydrogen, and carbon dioxide. Anaerobic digestion is a process in which microorganisms break down organic material in the absence of oxygen.

Other forest thinnings	Woody Cellulosic	gasification	13.65	77.95
Paper and paperboard	MSW (Cellulose)	gasification	15.82	91.34
Pine	Woody Cellulosic	gasification	15.02	86.29
Plastics**	Other MSW	gasification	28.46	163.12
Poplar	Woody Cellulosic	gasification	15.08	86.84
Primary mill residue	MSW (Wood)	gasification	15.34	88.15
Rice hulls	Cellulosic	gasification	12.21	69.84
Rice straw	Cellulosic	gasification	12.26	70.38
Rubber and leather**	MSW	gasification	21.36	122.27
Secondary mill residue	MSW (Wood)	gasification	15.34	88.15
Softwood, natural, residue	Woody Cellulosic	gasification	14.86	85.41
Softwood, natural, tree	Woody Cellulosic	gasification	14.86	85.41
Softwood, planted, residue	Woody Cellulosic	gasification	14.86	85.41
Softwood, planted, tree	Woody Cellulosic	gasification	14.86	85.41
Sorghum stubble	Cellulosic	gasification	11.80	66.87
Sugarcane bagasse	Cellulosic	gasification	13.62	78.26
Sugarcane trash	Cellulosic	gasification	13.38	77.04
Switchgrass	Cellulosic	gasification	13.47	77.75
Textiles**	Other MSW	gasification	14.09	80.52
Tree nut residues	Woody Cellulosic	gasification	15.29	87.75
Wheat straw	Cellulosic	gasification	15.70	89.80
Willow	Woody Cellulosic	gasification	14.79	85.26
Yard trimmings	MSW (Cellulose)	gasification	13.68	78.61

Notes:

*Ag residues are classed as cellulosic for liquid biofuel conversions below. Food waste, manure, and other municipal solid waste not categorized as wood or cellulose is not considered to be convertible into liquid fuels.

**These feedstocks are included in BTS2016 but typically contain petroleum-based content so are excluded from the renewable biomass potential.

Source: Study on future of natural gas in California, prepared for California Energy Commission.[77]

Table 39. 2050 Conversion inputs for liquid biofuels

E3 Feedstock Type (Aggregated)*	Produced Biofuel	Conversion Process[xi]	Efficiency (GJ/dry ton)	Process Costs (2012$/dry ton)
Cellulose	renewable gasoline	hydrolysis	10.10	175.74
Cellulose	renewable gasoline	pyrolysis	8.08	206.49
Cellulose	renewable ethanol	hydrolysis	6.32	86.71
Cellulose	renewable diesel	pyrolysis	8.94	228.48
Cellulose	renewable diesel	biomass to liquids**	10.70	126.43
Cellulose	renewable jet fuel	pyrolysis	8.68	221.65
Wood	renewable gasoline	pyrolysis	10.78	206.49
Wood	renewable ethanol	hydrolysis	7.83	92.57
Wood	renewable diesel	pyrolysis	11.93	228.48
Wood	renewable diesel	biomass to liquids**	10.70	126.43
Wood	renewable jet fuel	pyrolysis	11.57	221.65

Notes:

*Agricultural residues are classed as cellulosic for liquid biofuel conversions. Food waste, manure, and other municipal solid waste not categorized as wood or cellulose was not considered to be convertible into liquid fuels.

**Biomass to liquids refers to thermochemical conversion using gasification plus Fisher-Tropsch synthesis of drop-in synthetic fuels.

Source: Internal analysis performed by Black and Veatch for E3 in 2016.[78]

[xi] Hydrolysis is the chemical breakdown of compound due to reaction with water.

6.2 Hydrogen

As described above, the availability of biomass feedstocks is not infinite, so another low-carbon fuel is sometimes necessary. Hydrogen, when produced through water electrolysis using zero emissions electricity,[xii] can be a low- or no-carbon fuel. In this study hydrogen has been used to varying degrees based on the scenario; hydrogen can be used in trucks (as a liquid), for industrial processes (as a gas), can be blended in the natural gas pipeline, and can be used in power plants (as a gas). In all scenarios this study assumed hydrogen was produced through electrolysis rather than the current practice of steam methane reformation, which produces additional GHG emissions.

E3 assumed no feedstock limitation on the production of hydrogen via electrolysis since water is relatively abundant. To quality as a low-carbon resource for this study, hydrogen must be produced with zero-emission electricity; this means that substantial hydrogen production would add substantial load to the electricity supply system. This significant load represents a major limitation on hydrogen production. In scenarios that include hydrogen consumption for electricity generation, retrofitting power plants for hydrogen consumption would require a retrofit cost adder of 25% of the fixed cost of a natural gas generator.

These limitations, added loads, and production flexibility were accounted for in the electricity supply analysis (i.e., using the RESOLVE model). The efficiency of hydrogen production, for both gaseous hydrogen production and liquid hydrogen production, are displayed in Table 40.

[xii] Water electrolysis produces hydrogen by chemically separating water molecules into hydrogen and oxygen gas. This process requires significant electricity input but produces no direct GHG emissions. The current practice of steam methane reformation is a chemical process in which methane and water produce hydrogen gas and carbon monoxide which is then reacted with water to produce carbon dioxide and hydrogen gas. This process creates GHG emissions from the combustion of the methane.

Table 40. Hydrogen electrolysis efficiency

	Efficiency of hydrogen electrolysis process (Hydrogen output per unit electricity input)
Gaseous Hydrogen	78%
Liquid Hydrogen*	62%
Note: *Liquid hydrogen is produced by compressing and liquifying gaseous hydrogen.	

In addition to producing hydrogen for use in end-use sectors, RESOLVE had the functionality to produce hydrogen for combustion within electricity supply. RESOLVE determine the amount of hydrogen consumption for use in electric supply that would result in lowest cost, compared to other electric supply options such as building excess renewables and curtailing them.

Although natural gas generators can burn pipeline gas with a small percentage of hydrogen blended into it, natural gas generators cannot combust pure hydrogen without some retrofits. Thus, in any scenario that included hydrogen availability for electricity generation, retrofit costs were applied to all existing (and new) natural gas generators which combust hydrogen for electricity generation. Since unused hydrogen supply effectively imposes a cost penalty in the form of increased electrolysis loads, this analysis limited the demand for hydrogen supply for each scenario to avoid an excessive additional cost.

7 Load shaping

7.1 Methodology overview

Electrification is a central pillar to achieving New York's long-term climate goals. Because electricity has historically been more expensive to store than other fuels such as natural gas or diesel, matching the hourly supply and demand of electricity is important to maintain electric system reliability. The scenarios in this study include adoption of electric vehicles and building systems which have the potential to change the hourly demand for electricity. This section describes the methods used in this study to convert annual electric load forecasts, calculated for each sector and end use device as described in Sections 2-6, into hourly electric load forecasts.

In this study, E3 scaled historical system load shape to future years, and this formed the basis of the hourly load forecast. In each scenario (Reference or the Decarbonization Pathways scenarios), scaled historical hourly system load was adjusted by accounting for new end-use loads identified by the demand analysis in each of the scenarios, as follows:

1. E3 started with historical hourly load data for the upstate and downstate regions; this historical hourly load data was calculated by averaging 5-minute historical load data available from the NYISO.[79] E3 used historical hourly load data from 2007-2012 to align with the calendar chronology of the renewable profile used in this study, and aggregated these data NYISO zone into upstate and downstate regions.

2. E3 projected she system load shape for forecast years was increasing historic hourly load to account for macroeconomic growth with no incremental electrification or efficiency measures. The macroeconomic growth factor was based on a New York state population growth forecast from 2017, which included

a compound annualized growth rate of 0.08%.[xiii] Load shapes representing electrification and efficiency measures were then calculated from forecasted end use load changes, and were applied to the scaled historical system load shape. The end use load shapes are described in further detail below.

3. E3 combined annual forecasted electricity demand by end use with normalized hourly load shapes by end use to create hourly end use load shapes in forecasted years:
    a. The difference between annual end use load from the Decarbonization Pathways or Reference scenarios and the annual end use load calculated from the hypothetical "macroeconomic growth" case calculated in step 2, above, was used to calculate an incremental load, specified for each end use device type, which represents the amount of load growth for this end use device type which is incremental to the "macroeconomic growth" proxy growth forecasted in step 2, above. If the annual electricity demand for an end use device type was projected to grow at a faster rate than the macroeconomic growth proxy, this incremental load is positive; this means there is electrification and load growth in this end use. If the annual electricity demand for an end use device type grows at a slower rate than the macroeconomic growth proxy, this incremental load is negative; this means the effects of energy efficiency in this end use are causing annual load to decline relative to the macroeconomic growth proxy (for example, lighting loads might decrease as bulbs are switched from less efficient incandescent technologies to light emitting diodes).

    b. The annual incremental load for each end use device type, calculated in step 3a, above, was multiplied by the hourly normalized load shape for the corresponding end use device type. For example, the incremental load for the residential space heating end use device type was multiplied by a normalized hourly profile representing space heating load; this profile converted annual electricity demand into hourly electricity load. After this multiplication, the hourly incremental load for each end use

[xiii] This macroeconomic growth proxy load was created prior to the availability of updated Cornell population forecasts included in this study. E3 tested a range of macroeconomic growth proxies and found that using an updated CAGR of 0.19% to align with the population growth rate assumed in this study would not affect significantly affect the resultant hourly load shapes, so the macroeconomic growth proxy was left as .08%.

device type was added to the hourly system load calculated in step 2 to calculate the hourly system load in the forecasted year.

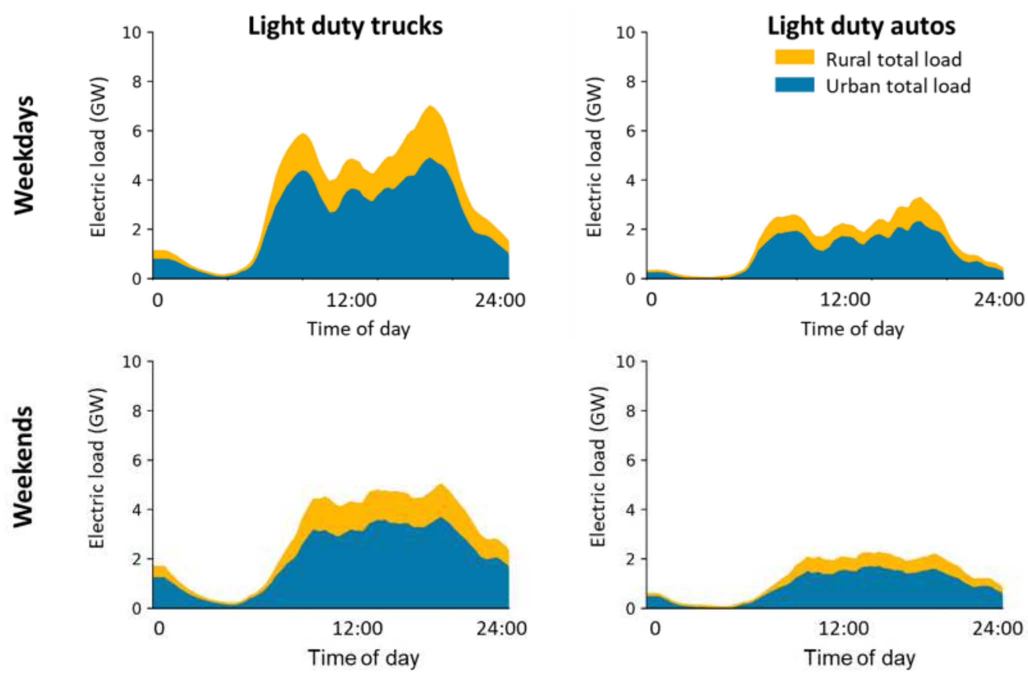
Note that this methodology accounts for both load increases, such as electrifying buildings and vehicles, as well as load decreases, such as increased appliance efficiency (for example, LEDs have significantly lower loads than conventional lighting technologies). This process generated hourly load shapes based on the changing composition of end uses. For each forecasted year, hourly loads were simulated for six sequential weather years (2007-2012) to align with the calendar chronology of the renewable profile library developed for this study.

To calculate hourly load shapes for two particularly impactful set of electrified end uses (light duty transportation and electric space heating), E3 used E3's RESHAPE Tool. RESHAPE is designed to capture the diversity of space heating and transportation loads under higher levels of electrification. The tool does this by representing a diverse housing stock, including geographically explicit weather data, and using empirical estimates of hourly energy usage where possible. RESHAPE includes modules for both transportation and buildings. E3 used RESHAPE to produce load shapes for the upstate and downstate regions. More narrow sub-geographies (e.g., a distribution substation) can also be represented but this was not feasible to do with the time and data available to perform this study. RESHAPE offers users the ability to vary key technology, weather, and behavioral parameters to examine hourly energy demand for both buildings and transportation in different circumstances. Varying these assumptions allowed E3 to explore a range of plausible electrification impacts.

7.2 Light-duty electric vehicles

Using the transportation module of RESHAPE, E3 identified light-duty vehicle electrification load shapes by using detailed regional trip data to simulate driving and charging behavior of thousands of drivers under various charging scenarios.[80] These simulations represent estimates of future electric vehicle charging behavior using historical trip data for fossil fuel vehicles, meaning the simulations are meant to represent the charging demands of electric vehicles which are representative of a broader future fleet, not the charging demands of currently existing or historical electric vehicles. The historical trip data includes information about daily trips taken by drivers in the local jurisdiction, including when drivers leave home; arrive at their destination (work, public or home) throughout the day; and when they return home. It also includes data on total miles driven during the day. These data were derived from the National Household Transportation Survey[80] (NHTS) and were split into weekend and weekday travel, as well as by drivers' home location type: rural, suburban, or urban. Aggregating these simulated charging sessions generated a load shape that captured diversity in driver behavior. Example simulated light duty vehicle load shapes are included in Figure 15. It is important to note that future load shapes might also be influenced by vehicle charging policy and design of transportation systems, and thus might result in different load shapes than the ones simulated in this study.

Figure 15. Example simulated light duty electric vehicle load shapes for urban and rural locations



Source: E3 analysis of sample weekday and weekend vehicle charging profiles for example urban and rural locations in New York State assuming 100% electric vehicle market penetration. These load shapes are representative, and the magnitude of the true electric vehicle load shape would depend on the market penetration of electric vehicles simulated in each region.

7.3 Freight vehicles and industry

Public data on freight vehicle and industrial electric load shapes are sparse. If real-time electricity prices fluctuate strongly in future years these loads might exhibit more sophisticated price responsivity than average residential or commercial load, but these loads might be constrained in their ability to respond to electricity prices by other variables. Without accurate, publicly available charging data it is difficult to calculate a representative charging profile for these end uses, so E3 used a flat load shape indicating that charging demand is consistent across all hours.

7.4 Hydrogen electrolysis and DAC

In this study, hydrogen electrolysis and DAC facilities operate flexibly and thus avoid operating during electric system peak load hours; see Section 7.6 for more details on flexible load in this study. While they contribute significantly to total electricity demand in scenarios with limited biofuel production (scenarios with high biofuel production have less need for hydrogen fuel or DAC to reduce GHG emissions from energy demand), electrolysis and DAC have little impact on incremental peak load. However, electrolysis and DAC loads can spur additional renewable energy capacity expansion as additional resources are developed to provide enough zero-emission energy to power these loads and stay within the electric sector emissions budget for that scenario. In this study electrolysis and DAC loads were characterized using the RESOLVE electricity model, which analyzed the optimal set of renewable and conventional electricity generating resources needed to meet electricity loads while staying within the electric sector emissions budget; see Section 8 for more information on RESOLVE.

7.5 Building load shaping

7.5.1 INTRODUCTION AND OVERVIEW

E3 used the buildings module within RESHAPE to simulate diversified space heating and water heating electric loads. The flexibility of the tool is meant to both allow users to examine the range of plausible load impacts from building heat electrification and directly align load shapes with assumptions and inputs in the PATHWAYS, RESOLVE, and RECAP models. The tool allows users to explore the load impact of building system electrification by varying key input assumptions, including:

+ Heat pump type
+ Rated annual heat pump efficiency

- Heat pump efficiency as a function of outdoor air temperature
- Choice of supplemental heat source (e.g., electric resistance vs thermal)[xiv]
- Level of building insulation
- Availability of thermal energy storage and flexible electric loads
- Climate and temperature extremes

E3 also used the buildings module to simulate a diverse, system-wide set of electrification load shapes. The aggregate impact of electrification on load cannot be easily estimated using individual building simulations. In practice, a system load shape will reflect heterogeneity in the building stock, variation in weather across space during a given hour, and the behavioral decisions of building occupants.

7.5.2 BUILDING STOCK CHARACTERIZATION

E3 used the 2012 CBECS and 2009 RECS Microdata files,[18,81] paired with data from the American Community Survey,[16] to characterize existing building stock.[xv] These data include the annual space heating energy demand by fuel for the population of buildings in the region. E3 sampled from those survey data to place representative RECS and CBECS buildings in all counties in a study region. This detailed characterization allowed E3 to calculate distinct load shapes for the upstate and downstate regions of New York.

7.5.3 SPACE HEATING CHARACTERIZATION

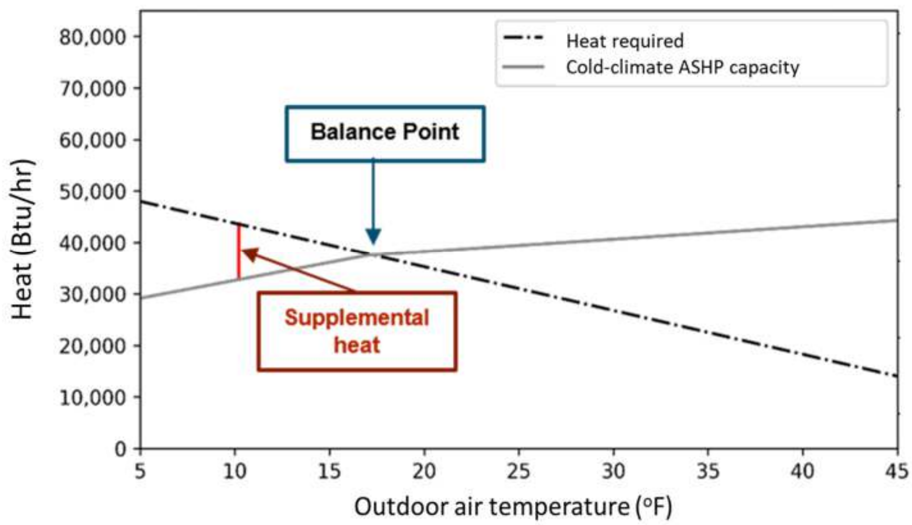
Space heating electrification has the potential to spur large changes in end-use load shapes at both the customer and system levels. Replacing combustion-based systems

[xiv] Air source heat pump performance declines in cold weather, with the potential need to have a supplemental heat source provide space heating when the heat pump is incapable of fully meeting space heating demand. This is discussed in further detail in Section 7.5.3.

[xv] Although it is more recent than RECS 2009, RECS 2015 published less detailed public use microdata, and thus more detailed RECS 2009 data were used to characterize existing building stock

with cold-climate ASHPs is an effective way to electrify space heating. However, although cold-climate ASHPs are more effective in cold temperatures than conventional ASHPs, as the outdoor air temperature drops, so too do the capacities of most cold-climate ASHPs (Figure 16). When cold-climate ASHPs can no longer meet building loads, supplemental heat is required. Electrification of space heating will add a large winter load to the New York grid, particularly during very cold weather. The magnitude of those peak loads depends on several key factors, including outdoor air temperature; levels of building insulation; and characteristics of cold climate ASHP, including performance as function of temperature, level of market penetration, and choice of fuel to provide supplemental heat. The RESHAPE buildings module simulated space heating loads under different combinations of those key parameters. Those parameters allowed E3 to test the sensitivity of electric loads to variation in those key assumptions, as well as ensure the underlying assumptions of PATHWAYS and the load shape tool (e.g., annual CoPs, building shell improvements) were matched.

Figure 16. Example ASHP performance and temperature



Source: E3 RESHAPE analysis of example cold climate ASHP output as function of outdoor air temperature in home which demands 48 kBtu/hr of heat at air temperature of 5°F.

E3 used the North American Regional Reanalysis (NARR) weather dataset from NOAA to develop region-specific weather files.[82] NARR provides 3-hourly outdoor air temperature for all North America in 32-km by 32-km square grid from 1979 through 2018. These data were used in the buildings module to analyze space heating loads in a variety of winter weather conditions, as well as generate loads that are weather matched to the renewables and base-system load profiles used in RESOLVE and RECAP. Another important use of geographically explicit temperature data is to capture regional diversity in heating loads, particularly during very cold weather where temperatures in populous areas of the study region can vary widely.

RESHAPE returns ASHP load and efficiency for any given weather year and set of assumptions.

Table 41 shows the realized annual and peak hour efficiencies for the heat pump portion of a space heating system, as well as the realized annual and peak hour efficiency for the entire system when accounting for electric resistance supplemental heat demand which are lower efficiency than the ASHP alone; this table assumed that 100% of supplemental heat required was served by electric resistance.

Table 41. ASHP peak and annual CoP

	ASHP CoP	System CoP
Low efficiency		
Peak CoP	2.0	1.3
Annual CoP	2.4	2.4
Medium efficiency		
Peak CoP	2.6	1.5
Annual CoP	3.2	3.1
High efficiency		
Peak CoP	3.2	1.7
Annual CoP	4.0	3.8
High efficiency with efficient building shell measures		
Peak CoP	3.2	1.8
Annual CoP	4.0	3.8
Source: E3 analysis of different heat pump types using RESHAPE analysis and New York state weather data		

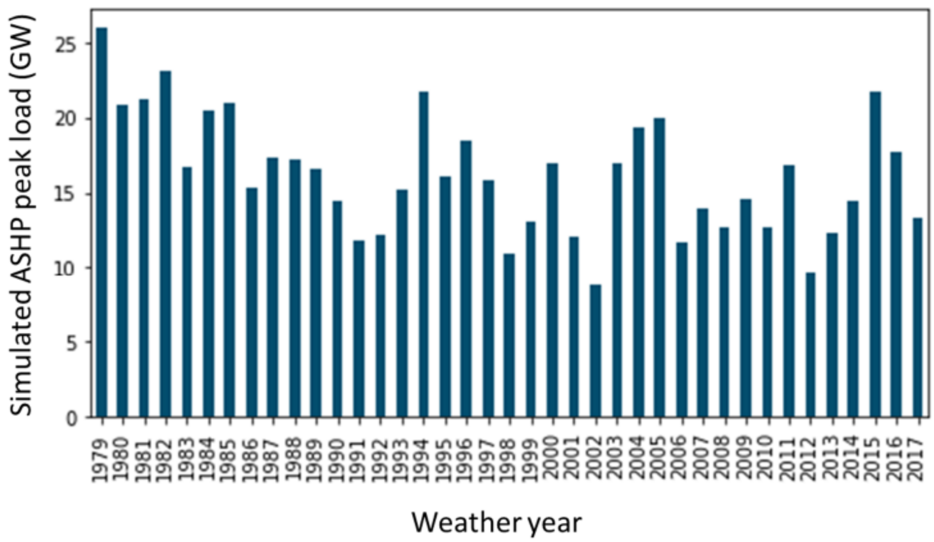
E3 used a mix of efficiencies of the heat pumps characterized in the table above to represent the diversity of installations across different building types and consumers. Low, medium, and high efficiency heat pumps can also be thought of as representing different technologies, but since this analysis was focused on the peak impacts of widespread building system electrification, it did not include specific technology decisions by building type.

E3 developed an initial set of load shapes to inform the RECAP analysis process. RECAP analyzed multiple years of weather data to identify the reliability implications of decarbonizing both electricity supply and electrification of end-uses. Using the model inputs noted above, E3 developed a set of ASHP loads for New York under 40 different weather years. Key inputs for those simulations, developed with the State project team as an illustrative representation of a diversified transition toward efficient electric heating, included:

+ **Heat pump efficiency**: 30% of systems installed are 'low' efficiency, 40% are 'medium' and 30% are 'high'.
+ **Building shell improvement**: consistent with market penetration of efficient building shells based on calculated stock rollover, E3 assumed a 35% reduction in space heating service demand for residential customers in 2050. Commercial buildings saw a 27% reduction in space heating service demand by 2050.
+ **Supplemental heat**: 40% of heat pumps were configured such that supplemental heat demanded was served by electric resistance, 30% were GSHP which require no supplemental heat, and 30% used fossil backup whose supplemental heat is served by a fossil heater.
+ **Sizing**: This analysis assumed heat pumps were sized for the 95th percentile of heat demand for each building (a larger heat pump sized for 98th or 99th percentile of heat demand would require less supplemental heat but would require greater initial costs).

Figure 17 shows simulated ASHP peak hourly loads for New York using 40-years of meteorological data and the ASHP assumptions described above. These results suggest that New York's electricity system could face large variations in space heating loads depending on the severity of cold snaps in any given year.

Figure 17. Simulated peak 2050 ASHP loads: 1979 - 2017 weather years



Source: E3 RESHAPE analysis to simulate potential ASHP peak loads under Decarbonization Pathways scenario levels of heat pump market penetration in 2050, using 1979-2017 weather year data and assumptions on heat pump efficiency, building shell improvement, supplemental heat source, and heat pump sizing as discussed above.

7.5.4 WATER HEATING CHARACTERIZATION

RESHAPE also includes a treatment of water heaters. Water heating demand is largely driven by occupant behavior, with one important driver of seasonal variation being changes in groundwater temperature. Because of the importance of capturing occupant behavior in analyzing water heating load shape, E3 used a combination of empirical and simulated load shapes to evaluate the load impacts of water heating electrification. The RESHAPE water heating simulation relied on two sources of empirical data. They include:

+ The Northwest Energy Efficiency Alliance's building stock assessment.[83] This study includes load shape data on both residential electric resistance and heat pump water heaters deployed in Washington, Oregon and Idaho

+ The California Commercial End-Use Survey (CEUS).[84] CEUS provides an average hot water usage shape by fuel for commercial buildings in California

E3 used empirical residential water heating load shape data from the Northwest Energy Efficiency Alliance study cited above and commercial water heating load shape data from the CEUS study cited above to represent the behavioral diversity of hot water demand. The data were mapped to simulated years to ensure the shapes were aligned by season and day of the week. When using Northwest and California data, E3 scaled the shapes using differences between the mean monthly groundwater temperature in those states and the equivalent temperature in the study region.

7.6 Flexible loads

7.6.1 INTRODUCTION AND OVERVIEW

In simulating electric system operations, RESOLVE can shift some amount of load to different times of day, subject to constraints on flexibility of each load end use, depending on the conditions on the electric system. This capability allows flexible load to play a role in intraday balancing by shifting load to hours of renewable surplus and away from hours of renewable deficit.

E3 assumed that by 2050, eight building end uses could contribute to meeting intraday flexibility needs. This is in addition to electric vehicle charging, hydrogen electrolysis, and direct air capture of CO_2 which could play a similar role and are discussed in sections 7.6.3 and 7.6.4. A summary of the flexible load end use categories is captured in Table 42.

Table 42. Percent of end use which is capable of shifting load

Sector	End use category	2030 - downstate (% flexible)	2030 – upstate (% flexible)	2050 - downstate (% flexible)	2050 – upstate (% flexible)	Hours Shiftable Daily
Residential	Space Cooling	10%	10%	60%	60%	3
	Space Heating	10%	10%	40%	40%	3
	Water Heating	10%	10%	40%	40%	3
	Refrigerators	20%	20%	60%	60%	2
Commercial	Space Cooling	20%	20%	60%	60%	3
	Space Heating	10%	10%	60%	40%	3
	Water Heating	10%	10%	60%	40%	3
	Refrigeration	20%	20%	60%	60%	2
Transportation	LDV EVs	25%	25%	50%	50%	12*
Other	Industry	0%	0%	0%	0%	0
	Electrolysis	100%	100%	100%	100%	12*
	Direct Air Capture	100%	100%	100%	100%	12*

Note:
*This is a simplification for vehicle charging, electrolysis, and direct air capture. More details on the flexibility parameters and constraints of transportation, electrolysis, and direct air capture are provided in sections 7.6.3 and 7.6.4.

7.6.2 BUILDING FLEXIBLE LOADS

E3 assumed a variety of building loads could be operated flexibly. For end use categories with non-electric supplemental sources (such as heat pumps with thermal backup), load can be shifted from the electric system to the non-electric supplemental fuel system, such as the gas system or the delivered fuels. For other electric load categories, in which the end use was not assumed to have a non-electric supplemental energy source, E3 relied on a set of parameters that, for each end use, represent the percentage of load that can be analyzed as “perfectly flexible” as a function of the number of hours that the load for the end use in question can be shifted. Perfectly flexible load represents load that can be shifted to any time of day. RESOLVE simulated a fraction of load as perfectly flexible such that the load flexibility was mathematically equivalent to being able to shift the load by a certain number of hours. The “perfect flexibility” parameters were derived through a statistical analysis of end use load shapes to determine the potential load impact of various durations of shifting potential.[85]

E3 adopted a somewhat conservative set of assumptions for space-heating load shift in buildings with no non-electric supplemental heat source. These shift assumptions were meant to be consistent with the amount of space-heating shift that could be accomplished during a very cold day in both upstate and downstate New York.[86] This approach was meant to ensure this study did not over-value the role of space-heating load shifting as a peak capacity resource in the RESOLVE. An example of the calculation to convert the percentage of total end use load which was assumed to be flexible for a limited number of hours to the “perfectly flexible” parameter as analyzed in RESOLVE is shown in Table 43; this table shows an example for the downstate region building end use device types in 2050. Using the example of space cooling below, if 60% of space cooling load is assumed to be flexible and able to shift by 3 hours, then for the purposes of RESOLVE analysis, 22% (60%*36%) of space cooling load can be to any time over the course of the day, while the remaining 78% is assigned to the space cooling load shape with no ability to shift between hours.

Table 43. Translation of flexible load assumptions to "perfectly flexible" parameter in RESOLVE: example for downstate region building end use device types in 2050

End use device type	End use load analyzed as flexible (%) A	Hours the end use load can be shifted (hrs) B	Percent of end use load which could be analyzed as "perfectly flexible" if all end use load were flexible for hours in parameter B (%) C	RESOLVE input assumption for percent of end use load which could be analyzed as perfectly flexible (%) (A*C)
Res Space Cooling	60%	3	36%	22%
Res Space Heating	40%	3	35%	14%
Res Water Heating	40%	3	31%	13%
Res Refrigerators	60%	2	16%	9%
Com Space Cooling	60%	3	28%	17%
Com Space Heating	60%	3	46%	27%
Com Water Heating	60%	3	35%	21%
Com Refrigeration	60%	2	16%	9%

Source: Column A and B are input parameters for each end use device type, while column C is derived through statistical analysis of end use load shapes.[85]

7.6.3 HYDROGEN ELECTROLYSIS AND DIRECT AIR CAPTURE

To minimize electric system costs,[xvi] the RESOLVE model will optimize when it chooses to generate hydrogen over the course of a day, subject to the required annual fuel production and the capacity of production facilities. E3 assumed that the average annual capacity factor of the hydrolysis plants was 25%; therefore, the overall production capacity for hydrogen would be four times the required annual production, which defines the maximum amount of electrolysis load that can take place in a single hour. Similarly, the RESOLVE model will optimize when it chooses to operate DAC facilities, subject to the

[xvi] See Section 8 for more details on RESOLVE

required annual capture of CO_2 and capacity limits. Similar to electrolysis, a 25% annual capacity factor was assumed for DAC operations, therefore, the overall capture capacity of CO_2 would be four times the required annual capture quantity, which defines the maximum amount of DAC load that can take place in a single hour.

Because E3 expects that the winter months will be most challenging in terms of available renewable generation, in this study both electrolysis and DAC load was limited to non-winter months (March to October). All load from electrolysis and DAC was assumed to be in upstate New York, to avoid additional load in the more constrained downstate region.

7.6.4 ELECTRIC VEHICLES

RESOLVE simulated electric vehicles as having the capability to manage charging to reduce electric system costs but did not include a capability for EVs to discharge back to the grid, which is an important area for future analysis. In simulating electric system operations, RESOLVE simulated light-duty electric vehicle charging loads shifted to different times of day depending on electric system conditions, subject to driving demand and charger availability/capacity constraints. This allowed electric vehicle charging loads to play a role in intraday balancing, shifting demand to hours of renewable surplus and away from hours of renewable deficit.

The RESOLVE model optimized flexible EV charging such that there was enough state of charge[xvii] in the aggregate light duty EV fleet to meet simulated driving demand (simulated as described in 7.2) in each hour. RESOLVE had the capability to vary the charging capability of the flexible EV load to restore the state of charge. The flexible EV charging load was constrained by the maximum state of charge (total battery capacity of EV with flexible load capability) and minimum state of charge (10% of battery capacity for EV with

[xvii] State of charge is the amount of energy in a battery relative to its total capacity

flexible load capability), as well as ensuring state of charge of the aggregate EV fleet was high enough to meet simulated driving demand. In each hour simulated driving demand results in a decrease in the battery state of charge. The maximum charging capacity of the aggregate flexible EV load was determined by subtracting the number of vehicles which were on simulated trips from the total number of flexible EV vehicles. E3 assumed that by 2050, 50% of light duty EVs could charge flexibly and that all light duty EVs would have access to chargers during the middle of the workday.

8 Electricity generation

8.1 Analysis approach

This section describes the electricity generation sector analysis performed with the RESOLVE and RECAP models. It focuses on the data and methods that were used to benchmark the operations of the existing New York system and to characterize the costs of electric sector supply in New York, including the costs of building and operating various new generation and storage resources, upgrading and expanding transmission capacity, and operating existing resources. Work to estimate the costs and resource potential of renewable energy in New York builds on the NYSERDA *Clean Energy Standard White Paper – Cost Study ("CES Cost Study").*[87]

The RESOLVE model was used in this study to determine the least-cost pathway to meeting New York's electric sector targets, including the requirement under the CLCPA to generate 70% of New York's electricity from renewable resources by 2030 and eliminate greenhouse gas emissions from the state's electricity generation by 2040.[1] Designed specifically to address electric sector capacity expansion questions for systems seeking to integrate large quantities of variable resources,[xviii] RESOLVE layers capacity expansion logic on top of a production cost model[xix] to determine the least-cost approach to achieving renewable resource targets, accounting for both the upfront capital costs of new resources and infrastructure and the variable costs to operate the grid reliably over time.[xx] As the nature of electric system loads evolves over time, RESOLVE also captures

[xviii] Variable renewable energy resources include solar, onshore and offshore wind, and some types of hydropower.
[xix] A production cost model is a software tool which simulates electric grid operations and estimates the cost of dispatching a fleet of generators to meet electric load.
[xx] Capacity expansion planning is the practice of planning the addition of electric generation and transmission resources to meet electric load reliably and cost effectively.

key changes in demand-side behavior, such as increased flexibility in building loads and electric vehicle charging (see Section 7.6).

This study also used RECAP, a resource adequacy model that performs loss-of-load probability (LOLP) simulations, to assess the ability of renewable power generation and limited-duration storage to contribute to electric system reliability by determining the effective load-carrying capability[xxi] (ELCC) of wind, solar, and storage resources as a function of their penetration on the system. ELCC curves developed in RECAP served as inputs to RESOLVE, which ensures that the simulated New York system meets system-wide and local resource adequacy constraints.

8.1.1 MODELED COST CATEGORIES

RESOLVE's optimization solves for the least-cost system that meets all reliability, operating, and policy constraints, where total system costs are represented as the net present value of fixed and variable costs across the time horizon of the study. The major categories of cost included in RESOLVE's optimization are shown in Table 44.

[xxi] The ELCC of a generation resource is a measure of how much additional load can be met by the system while maintaining the same level of system reliability. For example, a 100 MW resource with an ELCC of 0.4 would indicate that 40 MW of load could be added to the system while maintaining the same LOLE.

Table 44. Categories of cost included in RESOLVE's objective function

Cost Type	Category
Fixed Costs	• Levelized all-in fixed costs* of new generation • Levelized all-in fixed costs* of new resource-specific transmission • Levelized all-in fixed costs* of new interregional transmission upgrades
Variable Costs	• Annual fuel costs of new & existing resources • Annual variable operations and maintenance (O&M) costs of new & existing resources • Annual start costs of new & existing resources
Notes: * All-in fixed costs include all initial costs of building a project, including land acquisition, labor, materials, and capital associated with financing, as well as the ongoing fixed costs during operations of the project.	

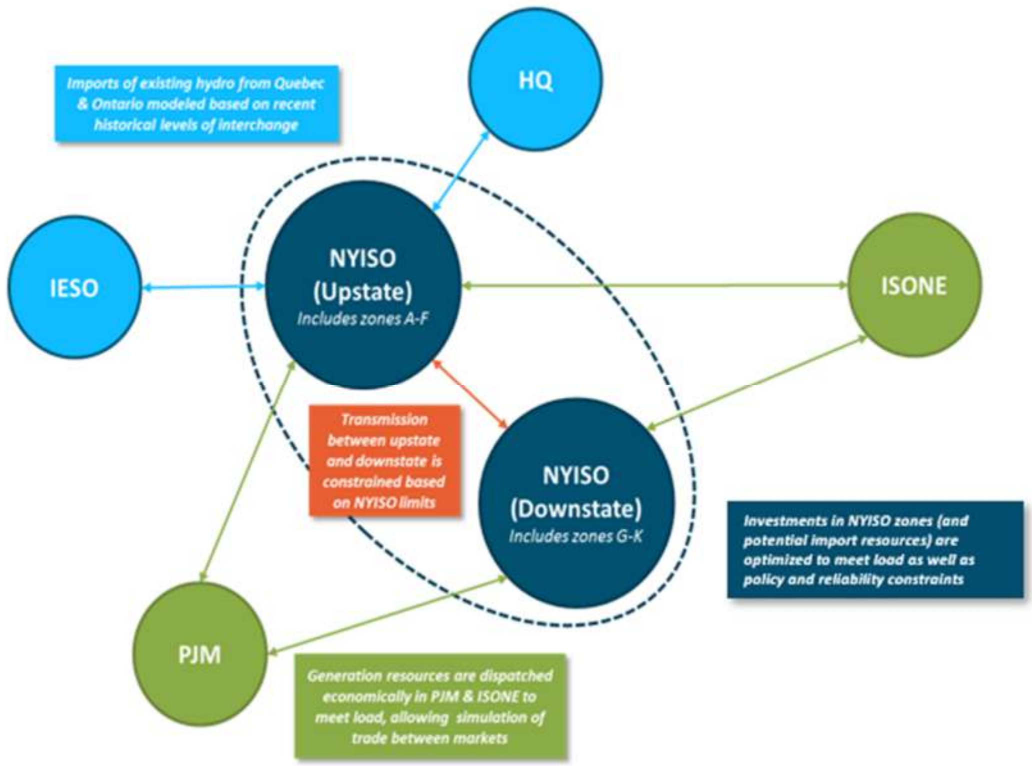
In each simulated year, RESOLVE selects from a range of new generation investments to meet future energy and capacity needs while meeting specified policy goals, layering these new investments on top of the existing resources assumed to remain on the system. In addition to so-called "conventional" resource options—for example, new gas combined cycles or combustion turbines—RESOLVE optimizes portfolios to include variable renewable resources, energy storage, and new dispatchable hydroelectric generation. To capture the impacts that each investment option has on system operations, RESOLVE simulates the hourly operations of the power system endogenously. The process of generating annual load forecasts and hourly load shapes, which are inputs to the RESOLVE analysis framework, is discussed in Section 7.

8.1.2 APPLYING RESOLVE TO NY

RESOLVE is a zonal resource planning model that has been configured to capture the operations of the New York electricity system as well as its interactions with neighboring power systems in the United States and Canada. For this study, RESOLVE was configured with six zones: two zones representing the upstate and downstate portions of the New

York electricity system and four zones representing the external markets that interact with New York. This configuration is shown in Figure 18.

Figure 18. Geographic configuration of RESOLVE



Within this configuration, RESOLVE optimizes investments only on behalf of the two New York zones[xxii] while optimizing the integrated operations of the entire system. Conditions and assumptions for the future loads and resources of neighboring markets are specified as inputs. RESOLVE's optimization capabilities allow it to select from among a wide range of potential new resources ("candidate resources"). The full range of resource options considered by RESOLVE in this study is shown in Table 45.

[xxii] The optimization of investments on behalf of New York includes the ability to develop remote resources (e.g., PJM wind or Canadian hydro) that are delivered to serve New York load, but does not optimize the build-out of new generation portfolios to serve load in external areas.

Table 45. Candidate resources considered in RESOLVE

Candidate Resource	Examples of Available Options	Functionality
Natural Gas Generation	• Simple cycle gas turbines • Combined cycle gas turbines (with or without carbon capture)	• Dispatches economically based on heat rate, subject to ramping limitations • Contributes to meeting minimum generation and ramping constraints
Nuclear Generation	• New nuclear capacity (upstate only)	• Treated as a must-run resource, i.e., is not able to ramp down and is not dispatched economically
Hydro Generation / Imports	• Upgrades of Existing In-state Hydro • New Canadian Hydro Imports	• Imports from Hydro Quebec (HQ) are budget-limited over course of year, but are highly flexible resources and contribute to balancing renewables output
Renewable Generation	• Utility-Scale Solar PV and Distributed Solar PV • Land-based Wind and Offshore Wind • Pipeline biogas • Hydrogen	• Dynamic downward dispatch (with cost penalty) of renewable resources to help balance load
Energy Storage	• Li-ion Batteries (>1 hr) • Pumped Storage (>12 hr)	• Stores excess energy for later dispatch • Contributes to meeting minimum generation and ramping constraints
Transmission	• Transmission expansion between upstate and downstate NY • Transmission upgrades required to access renewable resources	• Power transfer between zones is constrained by transmission limits • Some renewable resources will require additional transmission upgrades within the NYISO zone they are located

8.1.3 OPERATIONAL SIMULATION

RESOLVE's optimization includes the annual cost to operate the electric system across RESOLVE's footprint; this cost is quantified using a linear production cost model embedded within the optimization. The following are key components of the RESOLVE model and its representation of the operations of New York's electricity system:

+ **Zonal transmission topology:** RESOLVE uses a zonal transmission topology to simulate flows among New York and its neighbors. RESOLVE includes six zones: two zones capturing the New York system and four zones representing neighboring power systems.
+ **Aggregated generation classes:** rather than analyzing each generator within the study footprint independently, generators in each region are grouped together into categories with other plants whose operational characteristics are similar (e.g., nuclear, gas CCGT, gas peaker, and fuel oil peaker[xxiii]). Grouping like plants together for the purpose of simulation reduces the computational complexity of the problem without significantly impacting the underlying economics of power system operations.
+ **Linearized unit commitment:** RESOLVE includes a linear version of a traditional production simulation model. In RESOLVE's implementation, this means that the commitment variable for each class of generators is a continuous variable rather than an integer variable, which significantly reduces the amount of time the model needs to solve. Additional constraints on each generator class (e.g., minimum and maximum power output, ramp rate limits, minimum up and down time) are included to represent their operational characteristics and limitations.
+ **Co-optimization of energy & ancillary services:** RESOLVE includes reserve requirements in its generator dispatch, which is co-optimized to meet load while simultaneously reserving flexible capacity within NYISO to meet the contingency and flexibility reserve needs across the New York zones.[xxiv]
+ **Smart sampling of days:** whereas production cost models are commonly used to simulate an entire calendar year (or multiple years) of operations, RESOLVE

[xxiii] "Peakers" is used very broadly in this study to refer to units with high heat rates and does not refer to a specific technology or to units below a certain capacity factor.
[xxiv] Ancillary services, such as contingency and flexibility reserves, are services necessary to maintain electric system reliability that are provided outside of day-ahead and real-time energy markets.

simulates the operations of the NY system for 45 independent days. Load, wind, and solar profiles for these 45 days, sampled from the historical meteorological record of the period 2007-2012, were selected and assigned weights so that taken in aggregate, they produced a representation of complete distributions of potential conditions. Daily hydro conditions were sampled separately from the period 1970-2016 to provide a complete distribution of potential hydro conditions. This allows RESOLVE to approximate operating costs and dynamics over an entire year while simulating operations over a smaller subset of days.

+ **Reliability constraints:** in addition to the operational constraints and hourly simulation described above, RESOLVE includes both a conventional planning reserve margin (PRM) constraint and a multiday energy sufficiency constraint intended to capture the reliability challenges specifically associated with high-renewables systems. The PRM constraint is applied on an unforced capacity[xxv] (UCAP) basis and captures the reliability contributions of renewables and storage through ELCC curves developed in RECAP, E3's reliability model. The multiday energy sufficiency constraint is based on historical weather data and ensures that New York has sufficient capacity on the system to maintain reliability during extended periods of low wind and solar outputs.

8.2 Costs and input assumptions

8.2.1 EXISTING RESOURCE BENCHMARKING – NEW YORK

The existing resource data in RESOLVE has been benchmarked to align with NYISO Gold Book data and near-term expectations for new resource builds were also developed for this study. This benchmarking process has included the following:

+ Characterization of existing resources

[xxv] Unforced capacity is the capacity value of a generation asset after considering the asset's forced outage rate.

  - Benchmarking of E3 thermal generator database was performed to ensure alignment with database of thermal generators within the New York Control Area

- Biomass
  - Capacity and capacity factor assumptions were developed using the NYISO's New York Control Area database (see Table 46)
- Existing hydro imports
  - Available existing hydro generation imports was set to be consistent with amount included in the Clean Energy Standard accounting framework (10,400 GWh)[88]
- Existing onshore wind
  - The simulated generation shape for existing wind generators was derated to better align with historical performance and capacity factors
- Near-term renewable electricity (RE) builds
  - Firm builds: Implemented firm builds for 2020 and 2025 to align with current Large-Scale Renewables (LSR) solicitations and development expectations (see Table 47)[89]
  - Economic builds: Implemented constraint to limit in-state additions of renewable energy capacity in 2020 beyond projected firm capacity

Table 46. Biomass capacity and generation in 2019

Capacity (MW)	2019 Generation (GWh)	2019 Capacity Factor
327	2729	95%
Source: NYISO Gold Book[12]		

Table 47. Existing and planned renewable capacity (MW)

Region and Technology Type	2019 (Existing)	2020	2025
Downstate NY (G-K) Solar	32	57	329
Downstate NY (G-K) Wind	0	0	0
Upstate NY (A-F) Solar	0	252	1640
Upstate NY (A-F) Wind	1985	2163	3349
Source: NYSERDA Large-Scale Renewables Solicitations[12,89]			

8.2.2 EXISTING AND PLANNED RESOURCES – EXTERNAL ZONES

To enable evaluation of potential policy, the analysis isolated the impacts of New York policy changes and kept all other variables constant. This analysis assumed that the neighboring RTOs of PJM and ISONE will transition to a lower-carbon grid. To design the transition of each region, this study balanced the following objectives:

- In the Decarbonization Pathways scenarios, New York should not be able to rely on neighboring RTOs to balance its renewables output; other regions will also be transitioning to a lower-carbon portfolio and will have high amounts of renewables on their systems
- In the Reference scenario, imports of renewable power from neighboring RTOs to meet New York loads should be limited to avoid artificially lowering costs
- The renewables trajectories of external zones should recognize the relative positioning of each region's existing policy targets compared to New York

E3 applied the following steps to arrive at a renewables capacity trajectory for PJM and ISONE:

1. Aggregate existing state targets in each region as of December 2018 (Table 48), and then scale them up to match the increase in ambition in New York's policy goals (Table 49);[xxvi] for example, each region's 2030 targets increase by 1.4x (70% / 50%)
2. Estimate total new RE generation needed, after accounting for existing resources including hydro and biomass
   - In ISONE, this study assumed that new hydro imports from the Hydro Quebec region are also used to meet increasing RPS goals. This analysis relied on a recent study's estimate of 20 TWh[90] of new impoundment potential at low to medium costs in the region. [90] of new impoundment potential at low to medium costs in the region. After accounting for 2 GW (~11 TWh) of Canadian hydro available to NY as a candidate resource, the remaining 9 TWh are applied to ISONE by 2030 to meet its RPS goals.
3. Estimate wind and solar shares of total new RE renewables generation based on E3 market forecasting analyses.

[xxvi] Under the CLCPA, NY shifts from its 70x30 CES to a 100% emissions-free an emissions target in 2040. For simplicity, this study scaled the PJM and ISONE RPSs proportionally as if NY was pursuing a 100% RPS; in other words, this study doubled the PJM and ISONE targets as NY moves from its previous 50% CES to a 100% zero emissions electricity target.

Table 48. Baseline regional RPS goals

Region	Technologies	2030	2040
NY	All RE	50%	50%
ISONE	All RE	37%	43%
PJM	All RE	20%	20%
Sources: E3 analysis of existing state policies.			

Table 49. Scaled regional targets

		New targets		
Region	Technologies	2030	2040	2050
NY	All RE -> Zero Emission	70%	100%	100%
	Scaling Factor	1.4x	2x	2x
ISONE	All RE	52%	86%	86%
PJM	All RE	28%	40%	40%
Source: E3 scaling of PJM and ISONE RPS goals to increase in proportion to NY CLCPA goals				

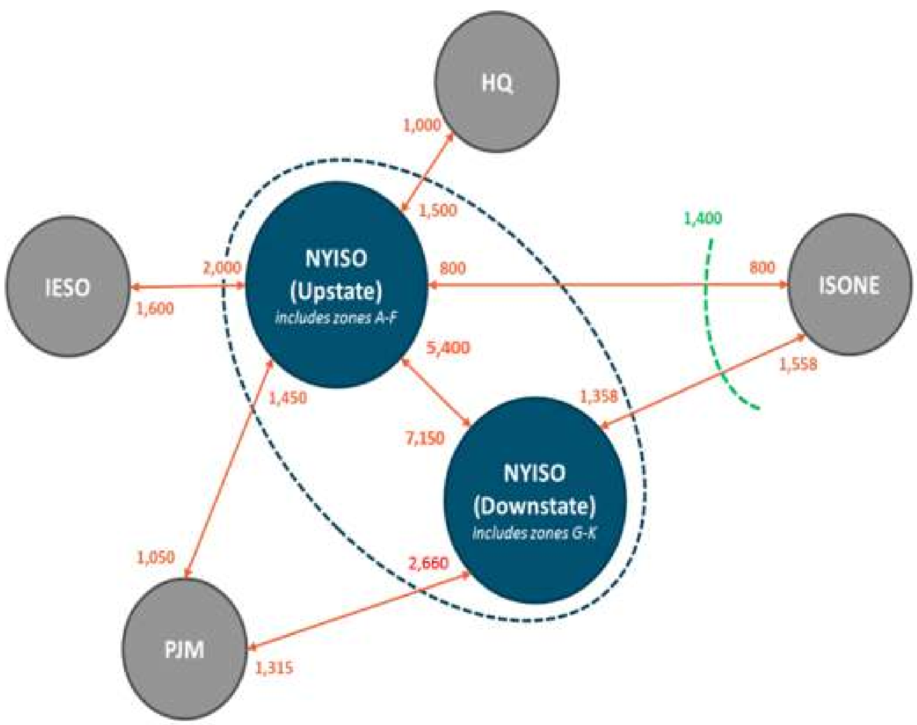
After estimating the wind and solar capacity additions in each region, E3 then applied a simplified approach to adding capacity and developing the remaining resource mix to meet load and reliability needs:

1. Build 0.25 MW of 4-hour battery storage for every 1 MW of solar PV
2. Assume a 20-year license extension for all existing nuclear capacity beyond their current 60-year licenses (aside from the planned retirement of Pilgrim in ISONE)
3. Retire all coal generators in ISONE by 2030, and all coal in PJM by 2050
4. Replace retiring coal and nuclear capacity on a 0.5:1 basis with new gas CCGTs (each MW of retiring coal is replaced with 0.5 MW of new gas CCGT)
5. Add gas peakers to meet any remaining PRM needs

8.2.3 TRANSMISSION

The transfer capacity of the existing transmission system between the six zones represented in this study was based on a capacity study for 2019-2020 by the New York State Reliability Council,[78] with an adjustment made to account for the additional transfer capacity between upstate and downstate New York associated with the announcement of the projects selected to meet the AC Transmission needs in 2019.[91,92] A schematic diagram displaying the transmission transfer limits is provided in Figure 19. RESOLVE also has the option to build additional transfer capacity between the upstate and downstate NY regions.

Figure 19. Transfer limits between RESOLVE zones



8.2.4 OPERATING CHARACTERISTICS OF THERMAL GENERATORS

RESOLVE represented thermal generating resources by aggregating units into classes by fuel and technology in each zone. This study relied on data from existing generators, as well as EIA assumptions for new generators, to develop operating characteristics for each aggregate generator class, provided in Table 50. For new generators selected by RESOLVE, generator classes share common assumptions across both upstate and downstate New York based on projected technology characteristics. For existing generators, because the inputs rely on data collected from actual units, technology characteristics vary by zone.

Fuel prices for thermal generators were developed using a combination of prices from NYISO's *Congestion Assessment and Resource Integration Study* (CARIS)[93] for the near-term and EIA's *Annual Energy Outlook*[40] forecast in the long-term. Annual fuel price projections were converted to monthly prices in RESOLVE using monthly shaping factors based on NYISO's CARIS forecast. Cost adders were developed to capture fuel delivery costs in each RESOLVE zone and were also based on the CARIS forecast. The resulting delivered gas prices in key years are shown in Table 51.

Table 50. Operating characteristics of each thermal generator class in New York

Technology	Vintage	Region	Minimum power output as % of maximum power output	Heat rate at maximum power output (Btu/kWh)	Heat rate at minimum power output (Btu/kWh)	Minimum up / down time (hrs)
Nuclear	Existing	Upstate	100%	10,200	10,200	24
Fuel Oil Peaker	Existing	Upstate	50%	12,100	14,100	1
	Existing	Downstate	50%	12,100	14,100	1
Gas Peaker	Existing	Upstate	50%	9,800	11,900	1
	Existing	Downstate	50%	10,800	12,800	1
	New	Statewide	40%	10,100	12,200	1
Gas Combined Cycle	Existing	Upstate	50%	7,300	10,000	4
	Existing	Downstate	50%	7,400	10,200	4
	New	Statewide	40%	6,500	8,600	4
Gas Combined Cycle w/ CCS	New	Statewide	40%	7,500	10,000	4

Sources:
E3 review of Energy Exemplar market data;
EIA documentation of electric generator cost and performance characteristics in AEO 2018.[94]

Table 51. Delivered natural gas price projections ($2018/MMBtu)

Zone	2020	2030	2040	2050
Upstate NY	4.14	4.60	5.04	5.69
Downstate NY	4.03	4.49	4.92	5.58
PJM	4.36	4.82	5.25	5.91
ISONE	4.76	5.24	5.67	6.33

Source:
E3 analysis of CARIS[95] and AEO forecasts[40]

Additionally, to analyze retirements of facilities based on economic considerations, an estimate of ongoing fixed costs for existing resources was required. E3 relied on a report prepared for the NYISO[96] which contained information about fixed operating and maintenance (O&M) costs and location-specific taxes. Using these estimates, E3 developed the inputs for existing fossil capacity in RESOLVE shown in Table 52.

E3 does not include nuclear units in its economic retirement logic. The retirement of upstate nuclear units are instead tied directly to the scenario definition.[xxvii] Nuclear retirements occur after 60 years in the Reference Case(s), while upstate units would be assumed to receive a 20-year license extension under the Decarbonization Pathways Scenarios. The ongoing costs of nuclear plant operations were benchmarked to current Zero-Emissions Credit (ZEC) prices, which reflect recent and ongoing plant investments and fixed costs.

Table 52. Capacity-weighted ongoing fixed costs of existing thermal generators

	Ongoing fixed costs of upstate existing thermal generators (2018$/kW-yr)	Ongoing fixed costs of downstate existing thermal generators (2018$/kW-yr)
Gas Combined Cycle	33	54
Oil and Gas Peakers	45	74
Source: E3 analysis of Analysis Group report prepared for NYISO[97]		

8.2.5 CANDIDATE RESOURCES: RENEWABLES POTENTIAL

The available renewable power resource potential in New York State was developed based on the CES Cost Study,[87] and the characterization of renewable power potential by NYISO zone in RESOLVE is provided in Table 53. The renewable potential estimates in the

[xxvii] The nuclear units located in downstate New York – Indian Point units 1 and 2 – will be retired in 2020-2021.

CES Cost Study were focused on 2030 and accounted for near-term development constraints (e.g. builds per year). These potential estimates were augmented and expanded for this study to account for resources that would be available to meet longer-term policy goals.[98,99] As part of that augmentation, solar resources were separated into three cost tiers in each zone. Onshore wind resources were also disaggregated into separate cost tiers to account for significant variability of interconnection costs. The wind and solar cost tiers are discussed in more detail in the cost section below.

Hourly generation shapes were developed using NREL's Wind Integration National Dataset (WIND) Toolkit[100,101] and NREL's System Advisor Model (SAM) simulator[102] for wind and solar resources, respectively. Hourly generation profiles were developed for each renewable resource in each NYISO zone to capture geographic and weather differences and associated resource diversity across New York State.

Table 53. Resource potential by technology and zone

RESOLVE resource name	Active potential (MW)	Capacity factor	Active potential (GWh)
NYISO_A_Wind	2,816	41%	10,103
NYISO_B_Wind	561	39%	1,921
NYISO_C_Wind	3,500	38%	11,541
NYISO_D_Wind	458	37%	1,491
NYISO_E_Wind	4,281	39%	14,718
NYISO_F_Wind	1,270	39%	4,342
NYISO_G_Wind	503	40%	1,773
NYISO_H_Wind	-	-	-
NYISO_I_Wind	-	-	-
NYISO_J_Wind	-	-	-
NYISO_K_Wind	78	45%	308
PJM-E_Wind	-	-	-
PJM-W_Wind	3,038	37%	11,214
ISONE_Wind	-	-	-
IESO_Wind	3,048	44%	11,878
HQ_Wind	3,000	41%	12,171
NYISO_J_Wind_Offshore	6,400	47%	26,297
NYISO_J_Wind_Offshore_2	24,800	48%	103,867
NYISO_K_Wind_Offshore	7,200	48%	30,460
NYISO_A_Solar	17,913	19%	30,188
NYISO_B_Solar	10,913	21%	19,661
NYISO_C_Solar	23,147	20%	40,793
NYISO_D_Solar	3,554	21%	6,486
NYISO_E_Solar	32,873	20%	58,161
NYISO_F_Solar	18,690	21%	34,784
NYISO_G_Solar	5,471	21%	10,087
NYISO_H_Solar	81	23%	162
NYISO_I_Solar	-	-	-
NYISO_J_Solar	-	-	-
NYISO_K_Solar	1,946	24%	4,075
NYISO_A-F_Solar_Dist	8,000	19%	13,585
NYISO_G-K_Solar_Dist	8,000	19%	13,585
NYISO_A-F_Hydro_Upg	84	35%	257

NYISO_G-K_Hydro_NPD	19	52%	86
NYISO_A-F_Hydro_NPD	633	54%	2,987
HQ_Hydro_CHPE	1,000	80%	7,008
HQ_Hydro_Tier1	1,000	80%	7,008
HQ_Hydro_New	2,000	65%	11,388
IESO_Hydro_New	2,000	65%	11,388
Source: CES Cost Study[87]; E3 augmentation.			

8.2.6 CANDIDATE RESOURCES: RENEWABLES COSTS

To develop cost estimates for candidate renewable power resources, E3 relied on New York-specific cost estimates from the CES Cost Study[87] in combination with cost decline trajectories from NREL's Annual Technology Baseline (ATB) projections.[103]

For onshore wind, a detailed review of cost components by wind site used to develop the supply curve in the CES Cost Study found that a number of wind sites had extremely high interconnection costs that were skewing the average upfront cost estimates upwards. To adjust for this, E3 further disaggregated the wind resources in each zone by interconnection costs, with three cost tiers corresponding to the total wind resource potential available at certain interconnection cost thresholds as outlined in Table 54.

Table 54. Onshore wind resources potential and cost by cost tiers

Category	Unit	Total*	Tier 1 <$250/kW	Tier 2 $250-$1000/kW	Tier 3 >$1000/kW
# of sites		370	168	88	114
Potential	MW	10,118	5,758	2,797	1,562
Avg Interconnection Cost	$/kW	$788	$118	$411	$4,255
2018 Capex	$/kW	$2,049	$1,975	$2,088	$2,325
Total Upfront Cost	*$/kW*	*$2,837*	*$2,305*	*$2,723*	*$6,830*
LCOE (2018)	$/MWh	$68	$50	$60	$159
LCOE (2030)	$/MWh	$83	$67	$77	$175

Note:

*LCOEs provided are illustrative and based on base cost assumptions. They are not potential-weighted and do not include out-of-state resources.

Source: E3 analysis of CES Cost Study,[87] NREL ATB projections.[103]

E3 also determined that the solar power resource potential in the CES Cost Study was developed with near-term development in mind but is likely overly conservative for a long-term study, since it was limited to sites within 2 miles of any road or 3 miles of an existing substation. E3 used the CES Cost Study solar power resource potential as an estimate of a Tier 1 block (lowest-cost tier) and expanded the area available for solar development, creating two additional tiers of solar potential. The interconnection costs were assumed to scale linearly as a function of distance from the nearest interconnection point. The total solar potential used in this study is still nearly an order of magnitude below NREL's estimate of the total technical potential for solar capacity in New York State (Table 55).

Table 55. Development of expanded solar power potential and cost tiers

Tier	Solar potential (GW)	2018 Capex ($/kWac)	Distance from interconnection point (miles)	Incremental area (sq miles)	Interconnection cost ($/kWac)
Tier 1	38	$1,411	<3	28.3	149
Tier 2	38	$1,411	4.2	28.3	256
Tier 3	38	$1,411	5.2	28.3	337
Total	114				
NREL technical potential	959				

Source: Tier 1 potential and cost from CES Cost Study,[87] Tier 2 and Tier 3 potential set as equal to Tier 1 potential with larger interconnection distances. The interconnection cost for Tier 2 and Tier 3 was calculated by scaling interconnection costs as a function of distance. NREL technical potential from an NREL report on renewable energy technical potential.[98]

The cost estimates for offshore wind were developed based on recent offshore wind solicitations and cost analysis of NY State sites prepared for this study,[19] and are compared with generic (non-location specific) estimates from NREL in Table 56.

Table 56. Comparison of New York offshore wind costs with NREL ATB techno-resource group 3 (TRG3) costs

	Capital cost ($/kW)	
	2030	2050
Study - Mid	$2,402	$1,928
Study - Low	$2,162	$1,735
NREL - Mid	$2,530	$2,075
NREL - Low	$2,052	$1,795

Sources:

Cost analysis performed for this study;[19] NREL costs from *2018* ATB techno-resource group 3 (TRG3).[103]

Renewables development will also require local transmission upgrades in each NYISO zone.[xxviii] The costs associated with these local upgrades, as well as the costs of any bulk upstate-downstate transmission investments, were derived from cost estimates of candidate projects from New York State Department of Public Service proceedings on transmission investments,[104] and scaled to assumed distances of zonal and interregional upgrades (e.g., upgrade costs are higher on a $/kW-mile basis in downstate NY, but lower on a $/kW basis due to lower assumed distances of line upgrades). See Table 57 for the transmission investment costs included in RESOLVE.

[xxviii] The amount of local transmission capacity upgrades required considers limited capacity that may be available in each zone as a result of announced thermal retirements (e.g. scheduled retirement of Indian Point nuclear generating station).

Table 57. Transmission investment costs in RESOLVE

Type and location	Transmission costs ($/kW-yr)
Local Upgrades	
Zone A	66
Zone B	58
Zone C	33
Zone D	49
Zone E	25
Zone F	16
Zone G	82
Zone H	66
Zone J	26
Zone K	32
Inter-regional Investments	
HQ to Upstate NY	79
PJM to Upstate NY	145
HQ to Downstate NY (CHPE)	290
Bulk Transmission Investment	
Upstate NY to Downstate NY	145
Source: E3 analysis of DPS cost estimates of candidate projects in the AC Transmission proceedings.[92]	

The cost estimates for battery storage were developed based on Lazard's *Levelized Cost of Storage* report[105] as well as NREL ATB long-term projections,[103] as shown in Table 58.

Table 58. Capital cost projections for battery storage technologies[xxix]

Technology	Component/Unit	2018	2030	2050
Battery – Li-ion	Capacity $/kW	$226	$105	$85
Battery - Flow		$1,374	$872	$868
Battery – Li-ion	Energy $/kWh	$313	$145	$118
Battery - Flow		$246	$156	$155
Sources: E3 analysis of Lazard's *Levelized Cost of Storage*[105] and NREL ATB long-term projections.[103]				

The cost estimates for candidate thermal generation plants such as natural gas CCGTs and CTs were developed using the demand curve study,[97] using region-specific estimates for upstate and downstate New York. The costs of new CCGTs with CCS in New York were calculated by multiplying the cost estimates of a new CCGT in upstate and downstate New York by the ratio between the NREL ATB 2018 cost estimates for a CCGT with CCS and CCGT without CCS.

The costs of new hydro imports from Hydro-Quebec were developed using recent cost estimates of current and proposed projects as reported in the press and in recent solicitations.[106,107] There are two primary options available for delivering new imported hydro power from Canada into New York: the construction of new transmission lines into upstate New York, and construction of the Champlain-Hudson Power Express (CHPE) line to deliver hydro power into downstate New York (directly to Queens). Both options would rely on the delivery of power from existing hydro impoundments in Hydro-Quebec.

The delivery of power from existing hydro impoundments into upstate New York was benchmarked to recent power purchase agreements (PPAs) of $59/MWh, with a cost breakdown of ~$48/MWh for energy and $11/MWh for transmission.[108]

[xxix] In this study, the costs of a 4-hour Li-Battery are projected to be $170/kWh in 2030, which is generally well aligned with the projections published in the NYSERDA Energy Storage Roadmap (see Figure 15). This study also assumes that Downstate storage costs will be 1.25x higher than Upstate storage costs, consistent with the Roadmap.

The transmission costs of CHPE reflect recent upward revisions to cost estimates of close to $3B, corresponding to a levelized fixed cost of $290/kW-yr, or ~41/MWh, which are additive to the energy costs of $48/MWh.[107]

There are additional options that would require the construction of new dams and would therefore be significantly more expensive. The all-in costs of building new dams and constructing lines to import hydro energy from Hydro-Quebec and Ontario were estimated by E3 to be $135/MWh and $145/MWh, respectively.[109]

8.2.7 OPERATION OF EXISTING AND CANDIDATE HYDRO RESOURCES

Operation of hydro resources is simulated based on a variety of constraints. The constraints that govern operations of the hydro power systems in the US and Canada differ:

+ U.S. hydro systems (NYISO, PJM, and ISO-NE) were simulated with a daily energy budget in each of the 45 simulated days. These systems were assumed to have limited inter-day storage capability. Daily budgets were sampled as part of the day selection process to match the historical distribution of hydro conditions observed in each system on a seasonal basis.
+ Canadian hydro systems (Quebec and Ontario) were simulated based on an assumed annual energy budget. This budget was assumed to be flexible (i.e., can be shifted freely among the days of the year), reflecting the large seasonal storage capability of the hydro systems in Quebec and Ontario. This seasonal storage capability is crucial for balancing systems that include large amounts of renewable sources with variable supply during periods of low renewable output. This approach was used for both existing and new Canadian hydro resources.

Existing hydro resources in Ontario and Quebec were assumed to deliver power to New York over existing transmission lines; additional investment in new hydro resources was paired with transmission expansion investments that would allow delivery of larger quantities of hydro power.

In addition to the flexible annual budget described above, the neighboring Canadian hydro power systems may also provide value to New York in their ability to store energy produced in New York during periods of surplus from renewable sources and deliver it back to New York during periods of higher demand. This type of seasonal storage and bidirectional flow may prove critical to balancing loads and generation in a future when power is produced largely from renewable sources. To capture this potential dynamic without a full representation of the Canadian hydro system, this study assumes that sufficient hydro storage is available in each province such that the existing transmission capacity can be fully utilized to transmit power in either direction.

9 Glossary of Acronyms

Acronym	Definition
ACS	American Community Survey
AEO	Annual Energy Outlook
ASHP	Air source heat pump
ATB	Annual Technology Baseline
BBTU	Billion British thermal units
BDT	Bone dry ton
BECCS	Bioenergy with carbon capture and storage
BEV	Battery electric vehicle
BLS	Bureau of Labor Statistics
BTU	British thermal unit
CAFE	Corporate Average Fuel Economy
CAGR	Compound annual growth rate
CARIS	Congestion Assessment and Resource Integration Study
CBECS	Commercial Buildings Energy Consumption Survey
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CES	Clean Energy Standard
CHPE	Champlain Hudson Power Express
CLCPA	Community Leadership and Climate Protection Act
CT	Combustion turbine
DAC	Direct air capture
DOE	Department of Energy
DOT	Department of Transportation
EFS	Electrification Futures Study
EIA	Energy Information Administration
ELCC	Effective load carrying capacity
EPA	Environmental Protection Agency
EV	Electric vehicle
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GSHP	Ground source heat pump
GW	Gigawatt
GWh	Gigawatt-hour

HDV	Heavy duty vehicle
HFCV	Hydrogen fuel cell vehicle
HHV	Higher heating value
HVAC	Heating, ventilation, and air conditioning
HQ	Hydro Québec
IESO	Independent Electric System Operator (Ontario)
IPCC	Intergovernmental Panel on Climate Change
ISO-NE	ISO New England Inc
kW	Kilowatt
kWh	Kilowatt-hr
LBNL	Lawrence Berkeley National Laboratory
LDV	Light duty vehicle
LHV	Lower heating value
MDV	Medium duty vehicle
MECS	Manufacturing Energy Consumption Survey
MMBTU	Million British thermal units
MMT	Million metric ton
MOVES	MOtor Vehicle Emission Simulator
MSW	Municipal solid waste
MW	Megawatt
MWh	Megawatt-hr
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
NWL	Natural and working lands
NYISO	New York Independent System Operator Inc.
NYSDEC	New York State Department of Environmental Conservation
NYSDOT	New York State Department of Transportation
NYSERDA	New York State Energy Research and Development Authority
ODS	Ozone depleting substances
OSW	Offshore wind
PJM	PJM Interconnection LLC
RECS	Residential Energy Consumption Survey
RPS	Renewable Portfolio Standard
SEDS	State Energy Data System
TBTU	Trillion British thermal units
TW	Terawatt
TWh	Terawatt-hour
VMT	Vehicle miles traveled
WWTP	Wastewater treatment plant

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