THE COOPER UNION FOR THE ADVANCEMENT OF SCIENCE AND ART
ALBERT NERKEN SCHOOL OF ENGINEERING

# Decarbonizing New York's Power Sector

By

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A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Engineering

Advisors
Professor George Sidebotham
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This thesis was prepared under the direction of the Candidate's Thesis Advisor and has received approval. It was submitted to the Dean of the School of Engineering and the full Faculty and was approved as partial fulfillment of the requirements for the degree of Master of Engineering.

Barry L. Shoop

Barry L. Shoop, Ph.D., P.E. – 9/25/2020

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Joshua Novacheck

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Sincerely,

Zachary Tzavelis

# Abstract

The Climate Leadership and Community Protection Act (CLCPA), signed by New York Governor Andrew Cuomo in 2019, specifies that the state's electricity system must be 70% renewable by 2030 and carbon-free by 2040. In this work, three bottom-up engineering cost models are constructed to study the feasibility of achieving these ambitious goals. The study first analyzes the historical operation of the grid in 2019 before analyzing two future power systems specified in the literature. A two-node model of New York State is constructed using publicly available datasets from the New York Independent System Operator (NYISO), Energy Information Agency (EIA), National Renewable Energy Laboratory (NREL), and Oak Ridge National Laboratory (ORNL). The production cost models are constructed using a commercial software tool (PLEXOS), which uses optimization techniques to find the minimum cost for operating a grid system. The models show that New York could come close to achieving both its power sector goals, but could fail to meet them due to insufficient grid flexibility. Despite failing to meet both goals, a power system that relies heavily on wind, solar, and nuclear could operate with approximately 20% of the current annual carbon-dioxide emissions and generation costs. Furthermore, sources of grid flexibility, such as short and long-duration storage and demand response, will be crucial to enabling New York to develop a power system that can reliably achieve its decarbonization goals.

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## Table of Nomenclature

ACC – Anthropogenic climate change

ATB – Annual Technology Baseline

CLCPA – Climate Leadership and Community Protection Act

FO&M – Fixed Operation and Maintenance

GHG – Greenhouse Gas

ISO – Independent System Operator

LCOE – Levelized Cost of Energy

NREL – National Renewable Energy Laboratory

NSRDB – National Solar Radiation Database

NYCA – New York Control Area

NYISO – New York Independent System Operator

RTO – Regional Transmission Organizations

SAM – System Advisor Model

SRMC – Short Run Marginal Cost

VO&M – Variable Operation and Maintenance

# Chapter 1 Introduction

This thesis examines the sustainable development of New York State's electric grid. Sustainable development meets the present needs of society without compromising the ability of future generations to meet their own [1]. Anthropogenic climate change is a severe environmental impact of human activity that presents an existential threat to humanity. Over the past several years, countries around the world have begun taking action to *decarbonize* their economies (reduce or eliminate emissions of greenhouse gases) beginning with the most impactful sectors such as power, transportation, industry, and buildings. Energy infrastructure is one of the biggest leverage points for decarbonization because of its deep interconnections with other sectors. Transitioning energy infrastructure, such as the electric grid, to cleaner and carbon-free energy sources while maintaining its affordability is critical to empowering people and ensuring that future generations can enjoy the same or better quality of life. Consequently, sustainable development solutions need to be feasible both from an engineering and economic perspective.

Bottom-up engineering cost models[1] are techno-economic models used in power system planning that focus on operating and developing the grid cost-effectively while meeting demand and reliability constraints. As a necessity, electricity needs to be affordable and available all the time. As jurisdictions around the world commit to decarbonizing their economies over time, power systems will need to evolve to achieve governmental policies and goals. For many jurisdictions, this will involve transitioning from fossil fuel energy sources, which can be turned on at the 'flick of a switch', to harvesting emissions-free but variable energy sources like solar and wind. Relying on these new, weather-dependent, intermittent energy sources will change the dynamics and structure of the grid in ways that need to be managed to ensure reliable and affordable service.

[1] "Bottom-up engineering cost models use engineering data and principles to represent detailed technical characteristics" p. 4 [46]

The objective (or problem definition) is to minimize the cost of operating and developing the power grid while meeting demand, policy, and reliability constraints. Techno-economic power system models such as NREL's Standard Scenarios study [2] attempt to answer this question for regions as large as the entire North American continent. Other studies such as McKinsey's study "The global relevance of New York State's clean-power targets" focus on New York State [3]. Similarly, this work is a techno-economic analysis for New York State which focuses on analyzing the technical feasibility of achieving the goals of the Climate Leadership and Community Protection Act (CLCPA). The CLCPA, passed in 2019, mandates that 70% of NY's load be served by renewable energy resources by 2030, and 100% of it be met by carbon-free sources by 2040.

This work describes how three production cost models were constructed and used to analyze how NY can achieve the goals of the CLCPA and compare the operation of the future system to today's system. First, a 2019 model was constructed and tuned to accurately reflect the historic bulk power system operation currently in place. Then, two possible future power systems were constructed based on results from the aforementioned McKinsey study and NREL's Standard Scenarios study respectively [2].

# Chapter 2 Climate Change

The underlying motivation for the energy transition away from fossil fuels is climate change. However, it is also encouraging that the economics of clean energy technologies are becoming increasingly competitive – so the transition makes sense for our planet, our species, and our wallets. To tackle the problem, humans must significantly reduce emissions from activities that throw Earth's natural systems out of balance. Understanding the basic mechanics of Earth's systems and the magnitude of the changes humans must make is a critical first step toward understanding effective solutions.

## 2.1 Earth's Carbon Cycle

Earth contains about 65,500 million metric tons of carbon, making it the fourth most abundant element on the planet [4], after Nitrogen, Oxygen, and Hydrogen. Carbon is stored mainly in rocks, but other major reservoirs are soil, fossil fuels, plants, ocean, atmosphere. Several processes control the flow between the reservoirs such as photosynthesis, ocean-atmosphere exchange, respiration, and decomposition. The ensemble of processes has historically kept Earth's temperature relatively stable, however, natural events have influenced the carbon cycle over millions of years. As tectonic plates shift and change the rate at which carbon flows outward from the interior of the earth, the climate can shift into warm or glacial periods.

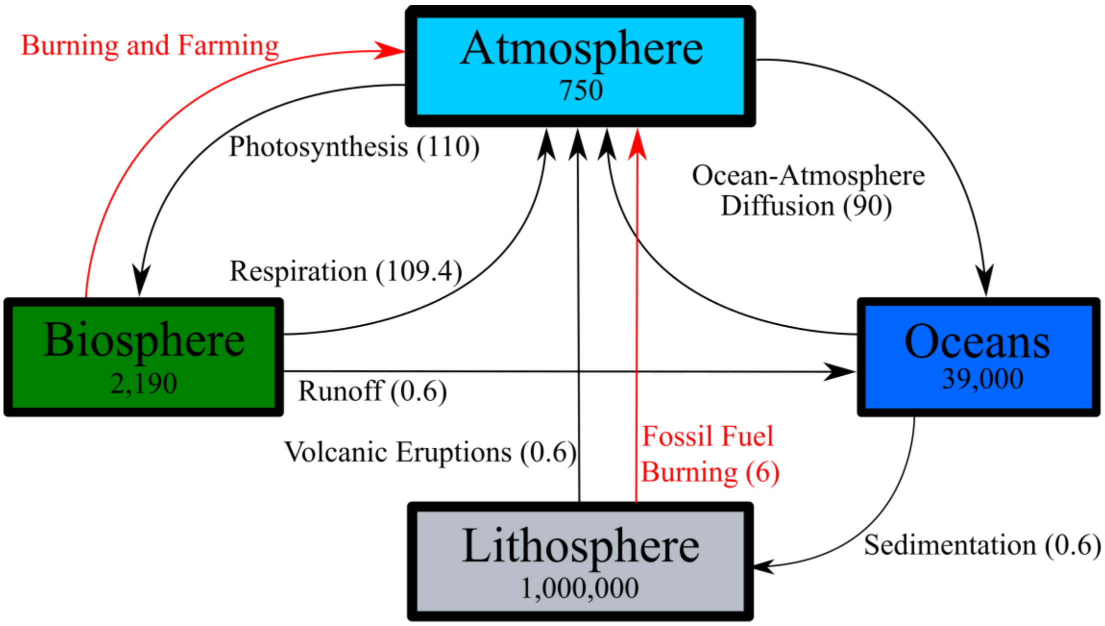


***Figure 2-1: Earth's Carbon Cycle****. Note: Reservoirs [GMt Carbon] and Flows [GMt Carbon/yr] in parenthesis [5]. This figure shows the mass reservoirs of carbon - not carbon-dioxide. Human emissions (unknown year) are 9 [GMt of Carbon /yr]; using the mass fraction of carbon in carbon-dioxide: 12/44, the amount of carbon dioxide equivalent that is emitted is 33 [GMt $CO2_e$/yr].*

*The slow carbon cycle takes* about 100-200 million years to circulate carbon; the flow of carbon from the atmosphere into rocks begins with rain mixing with atmospheric carbon to make carbonic acid by the time it reaches the Earth's surface. Once there, the acid dissolves rock and releases calcium, magnesium, potassium, or sodium ions that are eventually carried to the ocean by rivers. In the oceans, shell-building organisms (like corals) and plankton use the calcium ions to form calcium carbonate. When the organisms die, they combine with sediment to form limestone and its derivatives. This process accounts for how 80% of the carbon-containing rock is made, while the remaining 20% is formed when carbon from living things get buried and compressed in mud to form sedimentary rock like shale. Coal, natural gas, and oil can form instead of rock under special circumstances when there is a faster buildup of plant material than there is decay. The carbon returns into the atmosphere when volcanoes heat the rock turning it into silicate material and releasing carbon dioxide. Volcanoes emit between 130-380 million metric tons of carbon dioxide per year, which is about 100-300 times less than what humans emit by burning fossil fuels. In a separate process, the ocean and the atmosphere steadily exchange carbon-dioxide with the atmosphere [4].

*The fast carbon cycle* involves the flow of carbon between the biosphere and living things, in a cycle that occurs within the course of a single human's lifetime. Plants and phytoplankton use energy from the sun to take carbon dioxide and water to create sugar and oxygen. The carbon can then return to the atmosphere in four ways: plants can use the sugar, decay, burn, or be eaten, which all ultimately result in carbon getting back into the atmosphere [4]. While the fast carbon cycle moves 10-100 [GMt C/year] and the slow carbon cycle moves 0.01-0.1 [GMt C/year], human emissions are on the order of 1 [GMt C/year]. The magnitude of anthropogenic emissions is of similar order as the natural flows implying that human influences can have significant impacts on the Earth's carbon cycles [4].

## 2.2 The Greenhouse Gas (GHG) Effect Through A Thermodynamic Lens

One of the first concepts taught in an introductory thermodynamics class is the concept of a control volume, an imaginary boundary used for analyzing flows of energy from a system. The tool is used to understand and perform analysis using the fundamental laws of thermodynamics, the first of which states that energy cannot be created or destroyed - it can only be transformed from one form to another; an example would be the conversion of fuel (chemical energy) into electricity in a gasoline-fueled engine.

Figure 2-2 shows the Earth with a three-dimensional control volume completely encapsulating it. The boundary of the control volume is outside Earth's atmosphere, so the energy can only enter or leave by radiation. Focusing on only the flows of energy entering and exiting the control volume over time reveals an inflow of radiative energy from the sun (with a spectrum peaking in the visible) and outward flow of radiative energy from the Earth (infrared spectrum). An imbalance between inward and outward flow results in a rate of change of energy stored within the control volume.

Any imbalance between the flow of energy into and out of the Earth is critical – too low or high of a net-inflow can be catastrophic for life on Earth. The composition of the Earth's atmosphere plays a huge role in determining the rate of absorption of incoming solar energy and the rate of emission of outward flows. As anthropogenic emissions accumulate and overwhelm Earth's natural sequestration, the atmosphere thickens with denser gases that trap more of the radiation from leaving the Earth; this is commonly referred to as the 'greenhouse' effect. The effect is that the net flow of energy into the Earth increases resulting in increased global average temperatures among many other known and unknown impacts. Avoiding this outcome by decarbonizing human activities would attack the root cause of the problem, but other solutions like geoengineering could potentially offset some of the negative effects until widespread changes can be implemented globally.

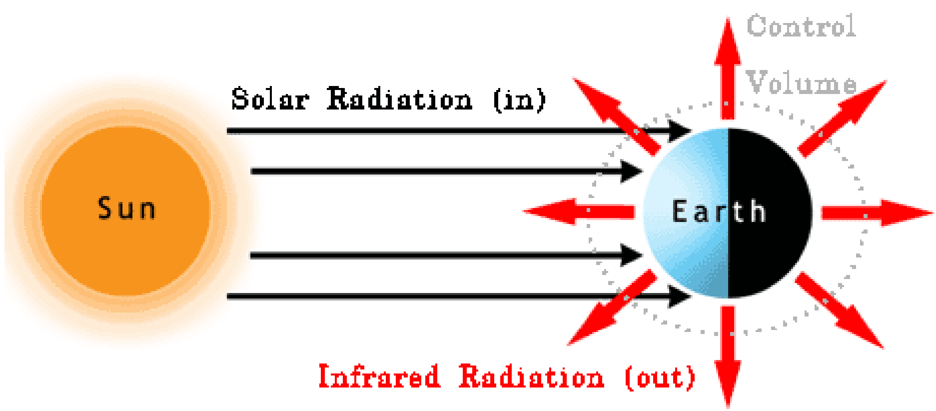


*Figure 2-2: Earth's Control Volume* [6]

## 2.3 Global GHG Emissions

Anthropogenic climate change (ACC) is the idea that human actions are causing significant changes in global climate including temperature, precipitation, and wind patterns [7]. Emissions of carbon dioxide and other gases from the combustion of fossil fuels to power buildings, transportation, industry, among other sectors are considered the primary driver. The National Academy of Scientists published a report in 2010 which found that 97-98% of the 1,372 climate researchers studied supported ACC findings laid out by the Intergovernmental Panel on Climate Change (IPCC) [8]. However, U.S public sentiment on the subject remains divided, with 2019 public opinion estimates indicating 53% of percent of the population believes in ACC [9].

The United Nation's Intergovernmental Panel on Climate Change (IPCC) assesses the science related to climate change and produces reports that communicate the science, risks, mitigation, and adaptation options. The five assessment reports that the IPCC has released since 1990 are widely regarded to be the most comprehensive climate change reports worldwide. Although the IPCC is an organization with 195 members from governments that are members of the United Nations or the World Meteorological Organization, thousands of people from all over the world contribute to the content produced in their reports. The review process is transparent and open to a wide range of views and expertise so that scientific agreement and further areas of research can be identified; the IPCC itself does not conduct research [10].

In the most recent Assessment Report (AR5) published in 2014, the report states that human influence on climate change is clear:

> *"Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now*

*higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane, and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century."(p.4 [11])*

Figure 2-3 shows the accelerating annual increase in emission of anthropogenic greenhouses gases, from 1.3 [%/yr] during 1970-2010 to 2.2 [%/yr] during 2000-2010. In 2010, anthropogenic emissions totaled 52 [GMt $CO_2$e], 72 [%] of which were from carbon-dioxide.

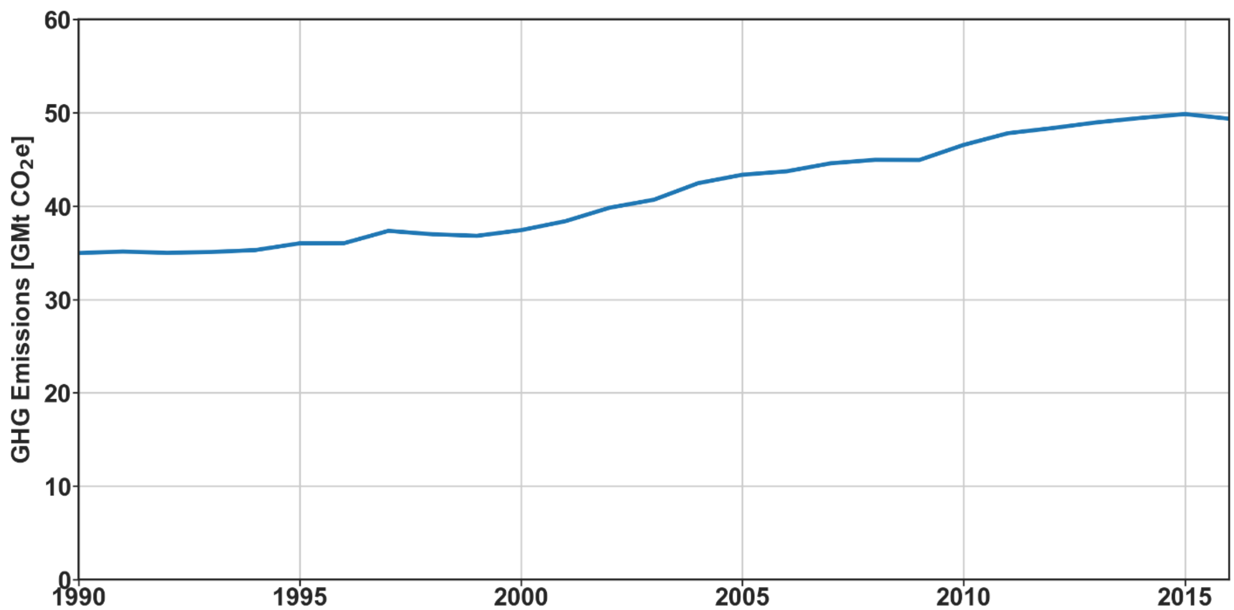


***Figure 2-3: Global Anthropogenic GHG Emissions [GMt $CO_2$e]*** *[12]* **.** *Note: Although it may seem like emissions peaked in 2015, more recent data from the 10th Emission Gap Report by the U.N. Environment Programme states that global GHG emissions were 55.3 [GMt $CO_2$e] in 2018.*

Table 2-1 shows the breakdown of global emissions by sector. Electricity and heat production account for 30% of total global emissions followed by the transportation sector at 16%.

*Table 2-1: Global Emissions [GMt $CO_2e$] by Sector (2016) [12]*

| Sector | GHG Emissions [GMt $CO_2e$] | % Of Global Total GHG |
|---|---|---|
| ***Electricity & Heat*** | **15.01** | **30%** |
| *Transport* | 7.87 | 16% |
| *Manufacturing Energy* | 6.11 | 12% |
| *Agriculture* | 5.80 | 12% |
| *Land-Use Change And Forestry* | 3.22 | 7% |
| *Fugitive Emissions* | 2.88 | 6% |
| *Industrial Processes* | 2.77 | 6% |
| *Buildings* | 2.72 | 6% |
| *Waste* | 1.56 | 3% |
| *Other Fuel Combustion* | 1.43 | 3% |
| ***Total*** | **49.36** | **100%** |

### 2.3.1 The Impact and Plan

The scientific community has concluded that emissions have caused increases in global average temperature and precipitation (Figure 2-4). The risk of abrupt and irreparable changes (in geological terms) to physical and ecological systems accelerates at 2°C and is high at 3°C. "Continued emissions of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive, and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks." [11]

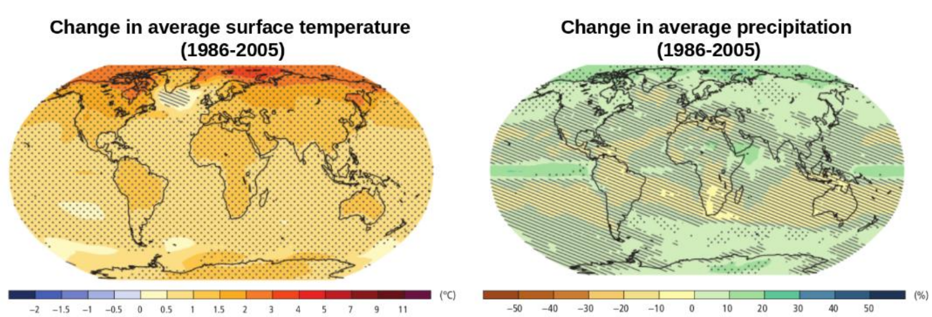


***Figure 2-4: Observed Increases in Global Average Temperatures and Precipitation.*** *Source: [11] p.72*

The Paris Agreement, in effect since 2016, was a landmark agreement signed by 194 states and the European Union to limit the global temperature rise in this century below 2°C above pre-industrial levels (and peruse efforts to reduce it further to 1.5°C). Industrialized countries, like the United States, need to reduce greenhouse gas emissions at least 80% below 1990 levels by 2050 to stabilize $CO_2e$ concentrations at 450 parts per million to stay within the 2°C target. Each country submitted their goals in emission reduction through Intended Nationally Determined Contribution (INDC). The United States is the second-largest emitter after China, set an economy-wide target to reduce emissions 26-28% below 2005 levels by 2026 [13].

### 2.3.2 United States Emissions

The electricity generation sector produced the most GHG emissions in the United States in 2015. Table 2-2 shows that electricity generation emitted 1.95 [GMt $CO_2e$], constituting 29% of total emissions in 2015, which is approximately 3.4% of global total emissions.

***Table 2-2: USA Economy-wide Emissions.*** *Source: Our World In Data [14].*

| Sector | GHG Emissions [GMt $Co_2e$] | % Of USA Total GHG Emissions | % Of Global Total GHG Emissions |
|---|---|---|---|
| ***Electricity & Heat*** | **2.15** | **37%** | **0.75%** |
| *Transport* | 1.71 | 29% | 0.59% |
| *Buildings* | 0.50 | 9% | 0.17% |
| *Manufacturing Energy* | 0.43 | 7% | 0.15% |
| *Agriculture* | 0.38 | 7% | 0.13% |
| *Fugitive Emissions* | 0.29 | 5% | 0.10% |
| *Industrial Processes* | 0.22 | 4% | 0.08% |
| *Waste* | 0.13 | 2% | 0.05% |
| *Other Fuel Combustion* | 0.09 | 2% | 0.03% |
| *Land-Use Change And Forestry* | -0.07 | -1% | -0.03% |
| ***Total*** | **5.83** | **100%** | **2.03%** |

#### 2.3.2.1 Policies

In 2019, The Trump Administration announced withdrawal from the Paris Agreement because of the “unfair economic burden imposed on American workers, businesses, and taxpayers by U.S. pledges made under the Agreement”. However, they also mention “the United States will continue to research, innovate, and grow our economy while reducing emissions and extending a helping hand to our friends and partners around the globe" [15].

### 2.3.3 New York State Emissions

New York State's emissions constituted about 3.52% of the country's total emissions and 0.42% of global emissions in 2016. The transportation sector and residential sector emissions are larger than those in the electricity sector – a notable difference from the country-wide values in Table 2-2 which lumped together electricity and heat production. The electricity sector contributed 13% of the state's total emissions, which is 0.48% of the total country's emissions, and 0.06% of global anthropogenic emissions. Even though the electricity sector is the third-largest emitter by sector, there will be increasing dependence on the power sector with the electrification of transportation and heating/cooling of residential and commercial buildings.

***Table 2-3: New York State Greenhouse Gas Inventory (2016).*** *Source: NYSERDA GHG Inventory [16]*

| Sector | GHG Emissions [MMt $CO_2$e/Yr] | % Of NY Total GHG | % Of USA Total GHG | % Of Global Total GHG |
|---|---|---|---|---|
| *Energy* | 172.8 | 84% | 2.96% | 0.35% |
| *Fossil Fuel Combustion* | 167.28 | 81% | 2.87% | 0.34% |
| *Transportation* | 73.23 | 36% | 1.26% | 0.15% |
| *Residential* | 30.66 | 15% | 0.53% | 0.06% |
| ***Electricity*** | **27.72** | **13%** | **0.48%** | **0.06%** |
| *Commercial* | 20.57 | 10% | 0.35% | 0.04% |
| *Industrial* | 10.15 | 5% | 0.17% | 0.02% |
| *Net Imports* | 3.82 | 2% | 0.07% | 0.01% |
| *Other* | 5.6 | 3% | 0.10% | 0.01% |
| *Waste* | 12.8 | 6% | 0.22% | 0.03% |
| *Industrial Processes and Product Use* | 11.15 | 5% | 0.19% | 0.02% |
| *Agriculture* | 8.86 | 4% | 0.15% | 0.02% |
| ***Total (Inc. Net Imports of Electricity)*** | **205.61** | **100%** | **3.52%** | **0.42%** |

### 2.3.3.1 Policies

The Climate Leadership and Community Protection Act, which passed the U.S Senate and was signed by New York Governor Andrew Cuomo in the summer of 2019, specifies three power sector targets: 70% renewable electricity by 2030, 100% carbon-free electricity by 2040, and 85% reduction in GHG emissions by 2050 below 1990 levels (intermediate target: 40% by 2030). These are all power sector targets, not economy-wide targets [17]. In 1990, NY power sector emissions were 236 [MMt $CO_2$e], which means they will need to be less than 142 [MMt $CO_2$e] in 2030 and less than 35 [MMt $CO_2$e] in 2050. To achieve these goals the state plans to deploy 9 [GW] of offshore wind by 2035, 6 [GW] of distributed solar by 2025, 3 [GW] of energy storage by 2030, and a 60% increase in energy efficiency by 2030.

### 2.3.3.2 Notable Studies

In July 2019, McKinsey's Electric Power and Natural Gas Practice published "The global relevance of New York State's clean-power targets" [3]. The goal of the study was to understand the investment and system changes that would be necessary to achieve the state's decarbonization goals cost-effectively. They concluded that decarbonizing New York's power grid will not be enough for the state to reach its economy-wide greenhouse gas goals; building and transportation will also need to be decarbonized – most likely through electrification. Electricity demand will rise by a third, 51 [TWh], from 153-204 [TWh]. The model predicts that more than 60% of NY's electricity will come from wind and solar by 2040, which will require improving grid flexibility through a range of options including storage and demand management. Market structures may need to change to compensate conventional generators in a way so that they can serve as backup power when needed; batteries could also help in this regard. Transmission flows in 2030 and onward will become erratic and may flip direction from the general north to south flow occurring today; this might occur in the winter when the offshore wind in the south is greater than solar upstate. Critically, their model suggests that more renewables than what the state currently will be needed to achieve the goals*:* 17 GW of offshore wind, 11 GW of onshore wind, and 23 GW of utility-scale solar. Demand management, which is the incentivization of curbing the use of power, will also become more important to operating a grid with intermittent power supply. They estimate that new generation, storage, and transmission interconnections could cost an additional $30 billion by 2040 compared to a system with no decarbonization targets.

# Chapter 3 U.S Electric Grid

## 3.1 The Electricity Supply Chain

The electric grid is one of the most complex and regulated systems ever created by humans. At the most fundamental level, the grid is a network that transports electricity from generators to consumers. There are hundreds of thousands of miles of high voltage transmission lines, millions of miles of low voltage distribution lines crisscrossing the country, and over seven thousand utility-scale generators. Electricity today is mostly generated in bulk quantities by generators powered by natural gas, coal, nuclear, wind, solar, etc. Data for electricity generation by the primary source in the United States is depicted in Figure 3-1, and by technology group in Figure 3-2. Over one-hundred million customers in America use this electricity for a wide variety of purposes [18].

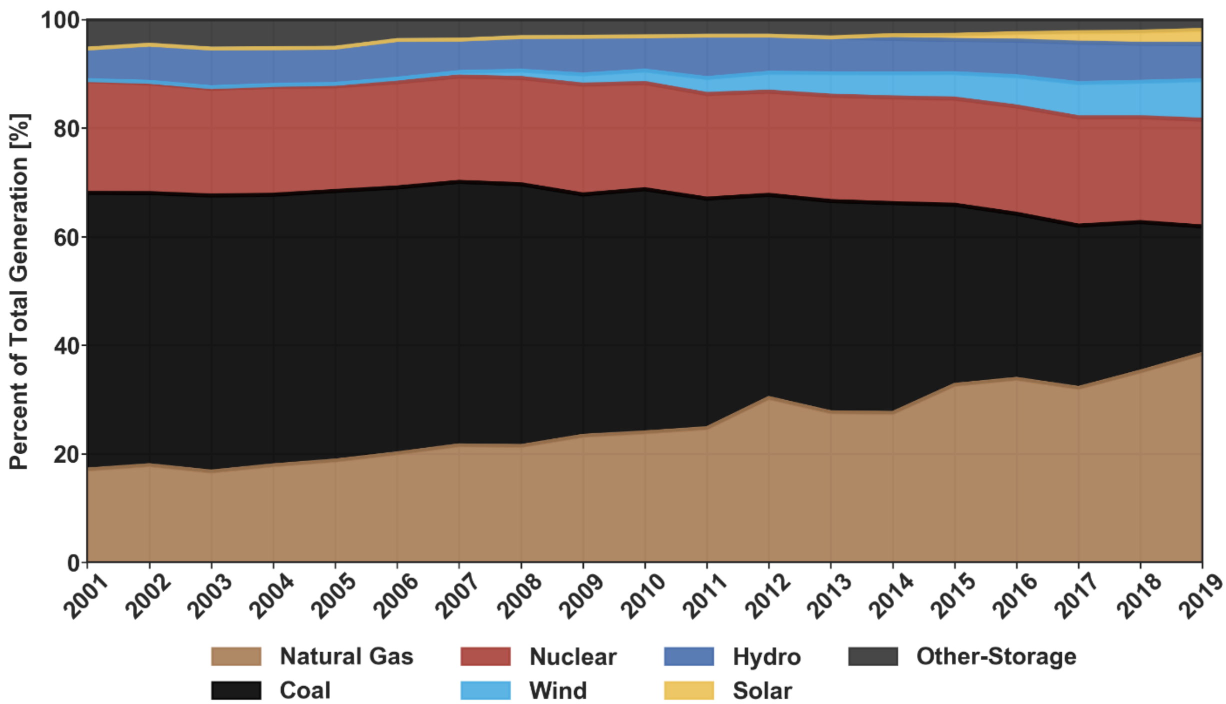


***Figure 3-1: US Net Electricity Generation Fraction by Fuel Source.*** *Data adapted from EIA Electricity Browser. [19] Note: The data represents the energy delivered by the power plants (not the source energy) and does not include transmission losses. The 'Other-Storage' category the difference between the energy generated by other energy sources and that stored in pumped storage.*

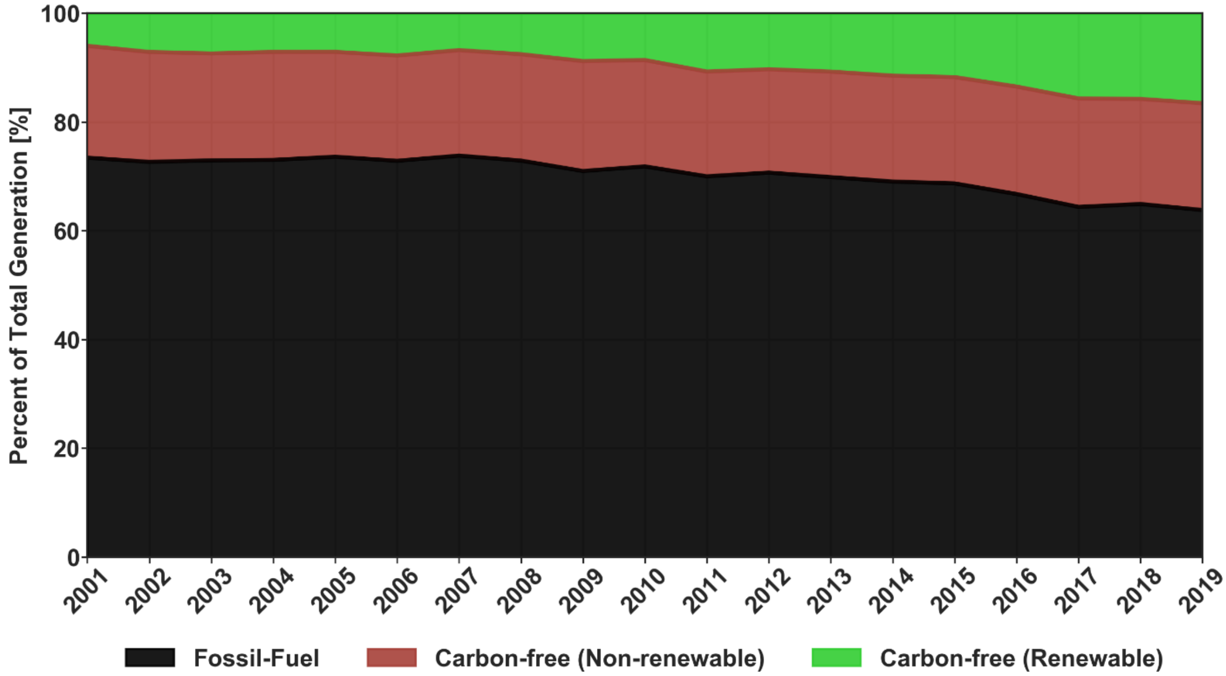


*Figure 3-2: US Net Electricity Generation Fraction by Technology Group. Data adapted from EIA Electricity Browser. [19] Note:'Other-Storage' category was included in the Fossil-Fuel group. 'Wind','Solar', 'Hyrdo' constitute the Carbon-free (Renewable) category. 'Nuclear' is the only fuel source in the carbon-free (Non-renewable) category.*

Figure 3-3 shows the grid's basic structure and how electricity flows from generators, through transmission and distribution lines, to the end customer. Utilities and independent power producers are the two types of entities that generate electricity for the grid; utilities also referred to as 'load-serving' entities, are also involved in the transmission and distribution of the generated power. The grid's transportation infrastructure can be broken into two components: transmission and distribution. Transmission infrastructure is used to transport electricity over large distances using high voltage lines (typically 66,000 Volts), while the distribution system (typically at 4000 Volts) carries the electricity to the end consumer where it is transformed to 120/240 split phase voltage before delivery. Utilities buy electricity from generators on the wholesale market (or generate it themselves) and then distribute and sell it to consumers on the retail market. In this study, only the transmission system and the respective wholesale electricity markets are modeled.

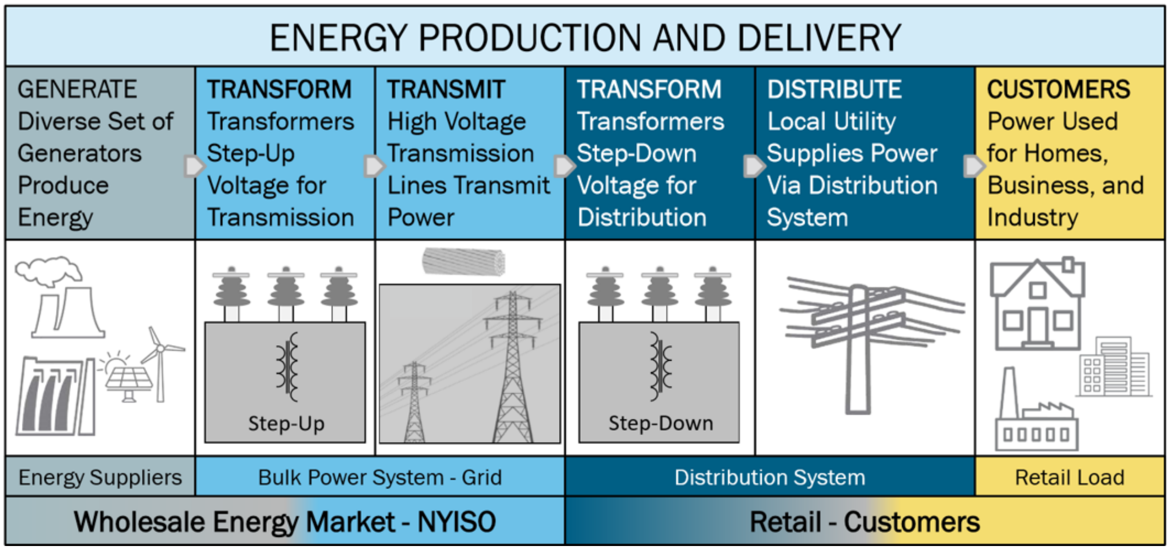


***Figure 3-3: The Electricity Supply Chain.*** *Source [20]*.

The contiguous United States consists of three large grids (interconnections): Eastern Interconnection, Western Interconnection, and The Electric Reliability Council of Texas (ERCOT) (Figure 3-4). These grids operate largely independently from one another, although there is some power transferred from one to the other. The operation of the grid in certain regions is managed by balancing authorities (utilities and regional transmission organizations (RTOs)), whose responsibility it is to maintain reliable electricity access in their region. According to the EIA, about 60% of the U.S electricity is managed by RTOs, seven of which are in the US, and three of which are in Canada. ERCOT is unique because its balancing authority, RTO, is the same entity and manages the same physical system, while the other regions may have more intricate organization [21]. Smaller, local grids are networked together to provide redundancy and efficiency and eventually scale to form an interconnection.

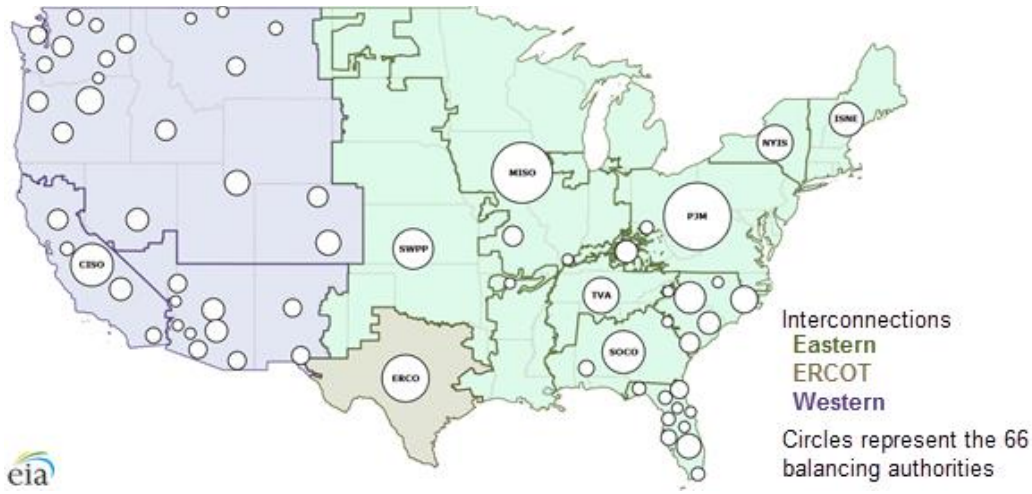


***Figure 3-4:US Interconnections.*** *The Contiguous US has three grids, called interconnections, operated by balancing authorities shown as circles [18].*

## 3.2 Introduction to Wholesale Electricity Markets

The United States is made up of a patchwork of electricity markets that fall into two categories: 'traditionally regulated markets' and 'market-regulated' (competitive) markets. Historically, electricity was traded in traditionally regulated markets using bilateral transactions[2] and power pool agreements[3] between utilities to achieve reliability and costs reductions. Utilities would make deals with each other to increase their reliability and take advantage of favorable economics from neighboring utilities. Utilities operating in these traditional markets are often vertically integrated monopolies, which means they own and operate generation, transmission, and distribution [22].

However, in the mid-1990's calls for more competition eventually lead to the creation of competitive electricity markets. The Federal Energy Regulatory Commission (FERC) passed Order No. 888, which made it mandatory for transmitting utilities to allow open access to their

[2] A bilateral transaction is an agreement between two parties to trade some quantity of energy for money at a specific point in time in the future.
[3] A power pool is a multilateral agreement in which participants give up control of generation and transmission to a common operator.

transmission lines. The order also promoted the concept of an independent operator, called an independent system operator (ISO) or regional transmission organization (RTO), to control the transmission system and foster competition for electricity generation among wholesale market participants. FERC Order No. 2000 encouraged utilities to join an RTO and consequently shifted the role of a utility to managing the distribution system. Today, RTOs balance demand and supply instantaneously, operate competitive electricity markets, ensure the reliability of the grid, and plan for transmission and generation expansion even if the organization does not own any transmission or generation. Figure 3-5 shows North American regions that belong to a competitive wholesale electricity market. Each region features a single RTO, multiple regulated utilities that own transmission and distribution, and multiple independent power producers that own generation assets like natural gas and solar plants [22]. For several market services, RTOs manage bids from electricity generators and load-serving entities, like utilities, and use optimization software to minimize the cost of producing energy while meeting all the physical constraints of the system. Constraints include meeting demand or maximum power that transmission lines can transmit at one time [22].

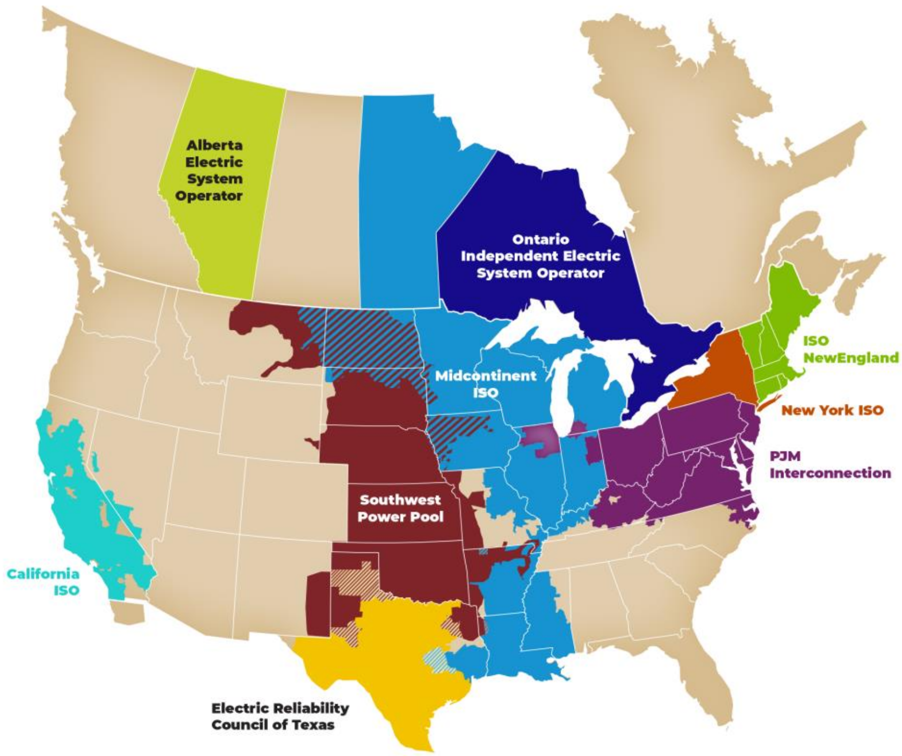


***Figure 3-5: North America's Competitive Electricity Markets.*** *Source: ISO/RTO Council [23]*

## 3.3 New York's RTO: NYISO

This research focuses on modeling the electrical power system in New York, which has a market-regulated electricity market run by the New York Independent System Operator (NYISO). In New York, most of the load-serving entities in NYISO have divested their generation [22]. Figure 3-6 shows the four different services that can be bought and sold on the wholesale market in New York to provide reliable and economic electricity service to customers. In the following sections, an explanation of the capacity market, energy market, ancillary services, and transmission congestion markets will be discussed. It is important to mention that not all RTO markets in the US have the same services available; for example, ERCOT does not have a capacity market.


***Figure 3-6: NYISO Electricity Market Services.*** *Source: NYISO Market Participants User's Guide [24]*

Since the electric grid must have a high degree of reliability, the delivery of services needs to be coordinated ahead of time. As a result, agreements for the delivery of various energy services can happen over various time scales – from years to seconds depending on the service. Most notably in the energy and ancillary service markets, bids and offers from market participants can occur on a day-ahead and real-time basis. In a day-ahead agreement in the energy market, a generator agrees to turn on their generator and provide the quantity of energy agreed and gets paid in return. However, because the amount of load that will be needed the next day at every hour is uncertain, the real-time basis allows for additional generators to be quickly dispatched to meet the load.

### 3.3.1 Energy Market

In New York, suppliers of energy can bid into the market or they can sell directly to purchasers, like a utility, using bilateral transactions. Energy suppliers can bid their energy in a market at a price defined primarily by the variable costs associated with their generator. Based on the bids and offers, the NYISO calculates a location-based marginal price (LBMP) for each region in Figure 3-7. Load-serving entities, like utilities, or other market participants can buy this energy at the LBMP. Depending on a wide variety of factors, such as generator type, an energy supplier may choose to bid energy in either or both the day ahead and real-time markets.

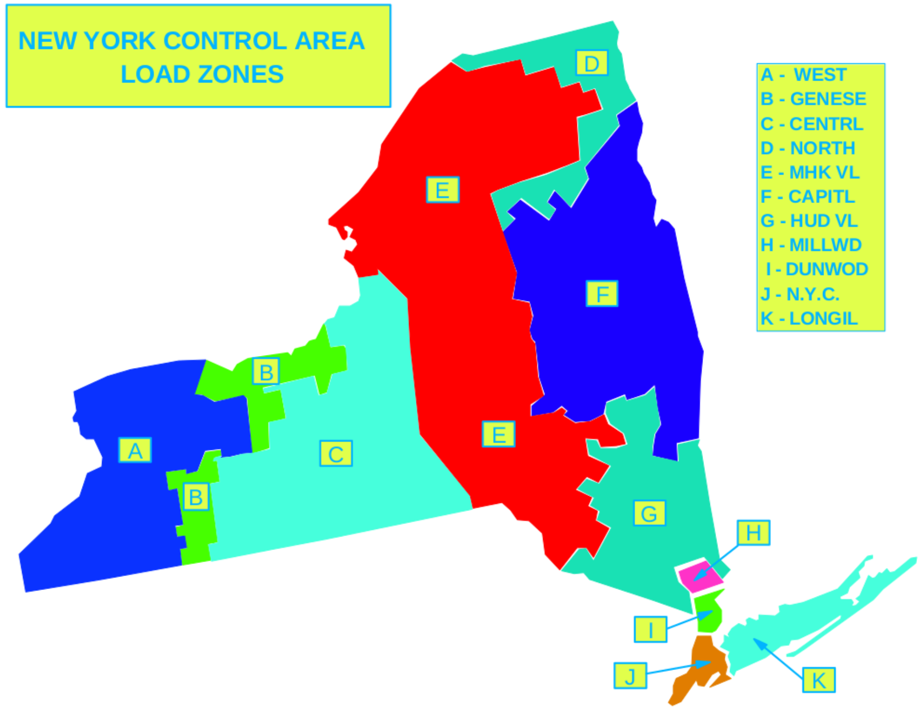


*Figure 3-7: NYISO Control Area Load Zones [24]*

Bilateral transactions, like a power purchase agreement, are the way energy transactions happen in the traditional market regions, but in New York, there are two ways to transact energy. A power purchase agreement is an example of a bilateral transaction between a utility seeking to buy renewable energy from a third party that builds, owns, and operates a plant. The third-party provides the electricity at a fixed rate over the length of the contract, which typically ranges between six to thirty years. Energy is the only service that will be modeled in this research.

### 3.3.2 Other Energy Services

Capacity markets exist to ensure there is enough generation capacity available to meet the expected peak load. Generators need to be available to provide power to meet load on a variety of time scales - from years to seconds. Technically, an installed capacity (ICAP) resource in NYISO is a generator or load facility that can supply or reduce demand on the system, and complies with certain reliability rules. Ancillary services, also known as essential reliability services, are energy services provided by suppliers that help maintain system reliability. There is a range of services that support the transmission of energy and reactive power, such as frequency control; frequency control services help maintain the AC frequency at 60 Hz. Transmission congestion contracts provide a way for market participants to pay a fixed cost ahead of time to ensure they have a transmission service in the case of congestion. The installed capacity, ancillary services, and transmission congestion contracts are not modeled in this study.

## 3.4 Power Generation Technologies

This section summarizes the current state of electricity-producing technologies in terms of both greenhouse gas emissions and levelized cost.

### 3.4.1 Emission Comparison (NREL LCA Harmonization)

A life cycle assessment (LCA) of electricity generating technology accounts for the emissions associated with the raw material extraction, processing, manufacture, transport of fuels, operation, and decommissioning, sometimes called a "cradle to grave" analysis. NREL has compiled a dataset of LCAs published on different power generation technologies between 1970-2010; because of some differences in methodology conducted between the studies, they also attempted to harmonize the published results to make fairer comparisons [25]. Figure 3-8 shows a comparison of the effective greenhouse gas emissions per unit of electricity (kWh) produced for different technologies. Coal, natural gas, and nuclear are considered non-renewable while all the others are renewable; coal and natural gas are fossil-fuels too.

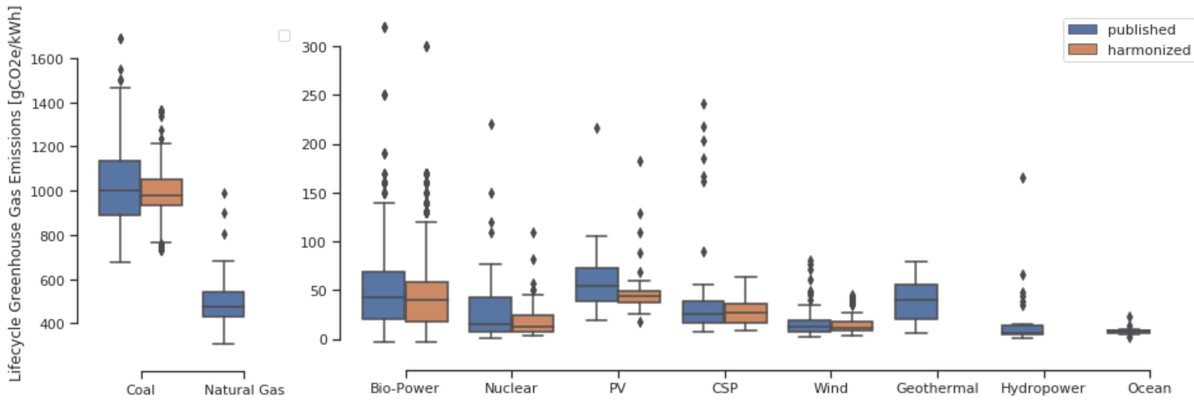


***Figure 3-8: Life Cycle Emissions of Power Generation (1970-2010)*** *[25]. Note: Some sources, like natural gas and geothermal, did not have harmonized values provided.*

Taking all associated factors into account (cradle to grave), non-fossil fuel-based technologies like solar, wind, and nuclear cause far fewer emissions than fossil-fuel technologies. Coal and natural gas roughly produce about 1-2 orders of magnitude more emissions per unit of energy than the other sources, which is what necessitated plotting them on a separate axis. Consequently, countries with fossil fuel-based power sectors could theoretically drop their power-sector emissions to 10% of current levels by switching to renewable sources assuming no change in the electricity demand. However, technical reasons cannot alone drive the transition to lower-emitting technologies; social, economic, and policy factors also play an important role [25].

### 3.4.2 Cost Comparison (NREL ATB)

As discussed in Section 3.3 , generators can provide multiple energy services but the most fundamental one is energy. Therefore, calculating the average cost of producing a single unit of energy (MWh), called the levelized cost of energy (LCOE), is often used to compare the economics of different generators (Figure 3-10). LCOE is calculated using a combination of technology and performance parameters including capacity factor, lifetime, capital expenditures, operational expenditures (such as fuel costs), grid connection costs, and finance cost. Figure 3-9 depicts the framework NREL's Annual Technology Baseline (ATB) for categorizing the costs and performance parameters needed to calculate the levelized cost of energy.

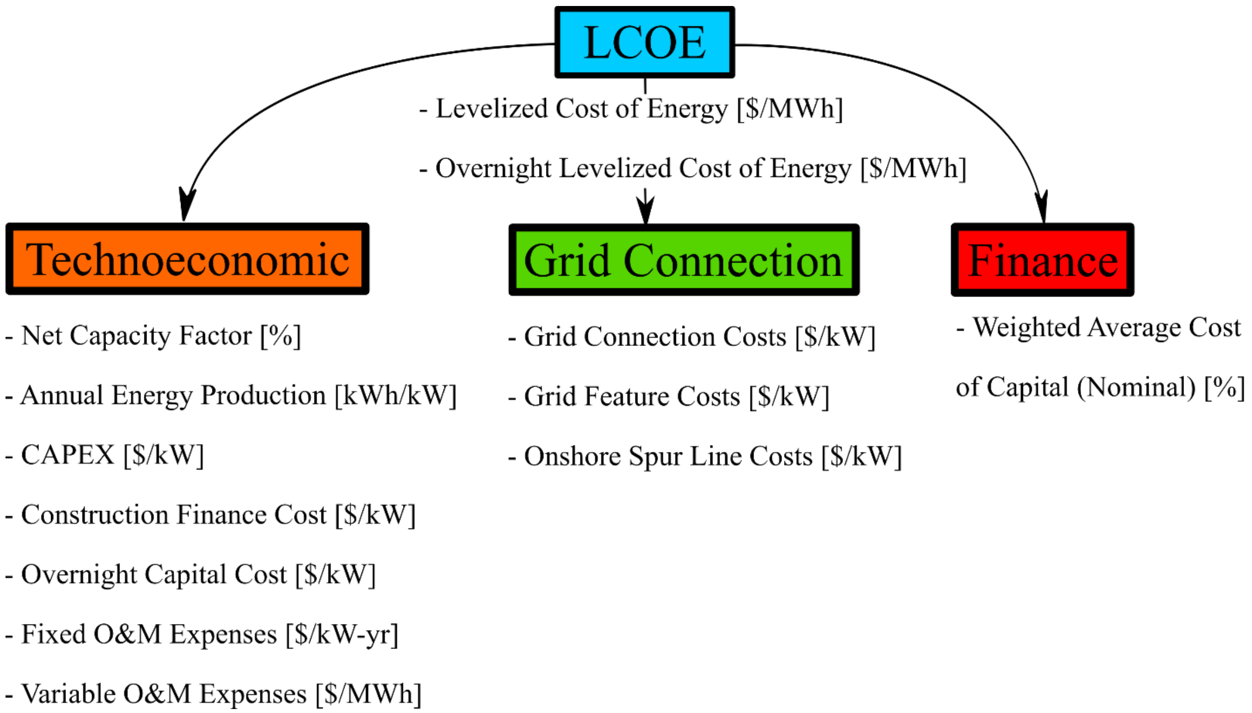


***Figure 3-9: Technology Cost Categories and Parameters for Calculating LCOE.*** *Source: NREL ATB2019 [26].*

Figure 3-10 depicts a comparison of LCOE data from NREL's ATB, which is a freely available repository of cost and performance parameters for technology across a range of resource characteristics, sites, fuel prices, and financing assumptions. Onshore wind has the cheapest lower bound of LCOE, making it the most cost-competitive resource in many geographies. The ATB includes current values as well as projections of how these parameters might change through 2050 over different scenarios, including R&D advancement [26]. Cost information and other generator parameters from the ATB are used in the New York study.

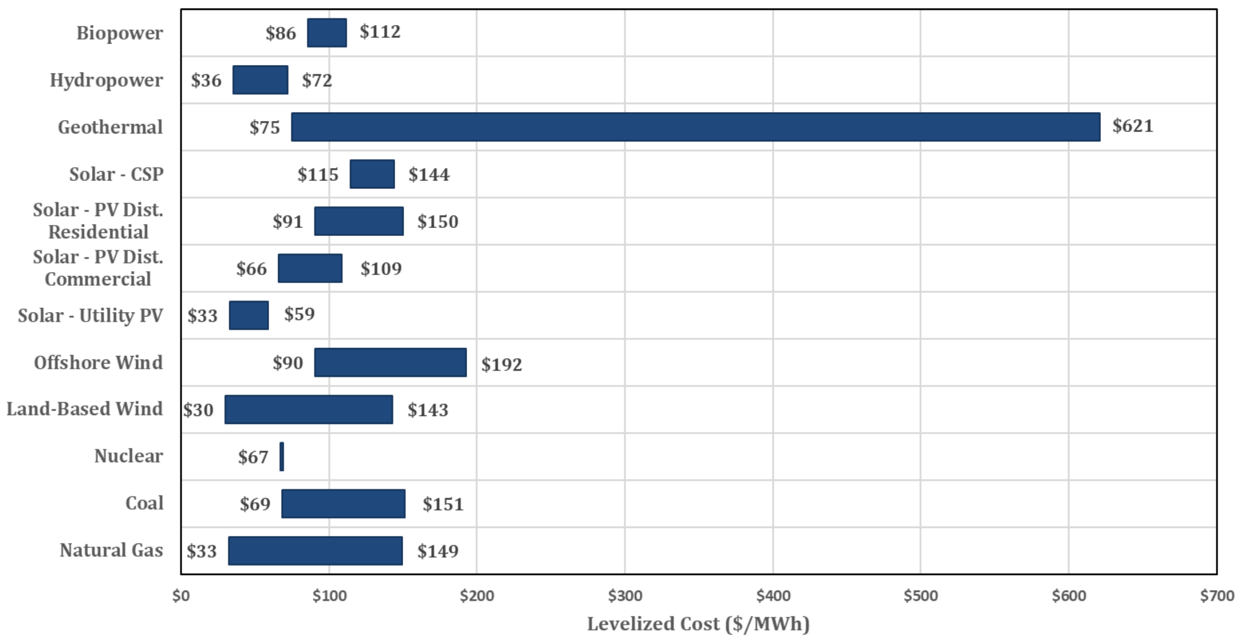


***Figure 3-10: 2019 ATB LCOE Range by Technology (2017 Based on R&D Financial Assumptions).*** *Source: NREL ATB2019 [26].*

With this background into the problem of global warming and the role of the electricity demand in modern society, the remainder of this thesis details a predictive study of the cost to operate the electricity grid with a network of generators that is assumed from literature studies. New York State is chosen as a case study since ambitious regulatory policies have been signed into law and the requisite datasets are available.

# Chapter 4 Methodology

Electricity must be affordable because it is a necessity for modern society. Since electricity service providers (utilities) price their services based on their costs, grid cost must be minimized to maintain electricity prices low for consumers. Modeling grid costs can help reveal the best way to minimize the costs of expanding and operating a power system. *Capacity expansion models* minimize the cost of installing and retiring generators and transmission, while *production cost models* minimize the cost of operating a power system. A simplified version of production cost modeling is often a component of capacity expansion modeling, but independently a production cost model provides higher fidelity of power system operation. This thesis is focused on constructing production cost models using the results from capacity expansion models from the literature.

## 4.1 Mathematical Formulation

In New York, the New York Independent System Operator (NYISO) operates the grid and associated markets and decides, among many other things, which generators will be turned on to economically meet demand. The goal of power system *operation* is to dispatch generators in such a way to minimize the total production cost while ensuring that supply matches demand, and generator and transmission physical constraints are met. Formally, this is a mixed-integer optimization problem that is generalized by the following equation:

*Equation 4-1*

$$C_{prod} = \sum_{t=1}^{T} \sum_{i=1}^{N} c_i * x_i(t), \ \min(C_{prod}) \ \ s.t \ \begin{matrix} \sum_{i=1}^{N} x_i(t) = L(t) \\ P_i^{min} * u_i \leq x_i \leq P_i^{max} * u_i \\ u_i \in [0,1] \end{matrix}$$

$$Where \ldots$$

$$C_{prod}\ [\$/h\ ] \ \equiv production\ cost\ of\ system\ (objective\ function)$$

$$c_i \left[\frac{\$}{MWh}\right] \equiv marginal\ cost\ of\ generator\ i$$

$$x_i(t)[MW] \equiv \ \ power\ produced\ by\ generator\ at\ time\ t\ (decision\ variable)$$

$$u_i \equiv binary\ variable\ for\ on\ (1)\ and\ off\ (0)\ state\ of\ generator\ (decision\ variable)$$

$$P_i^{max}\ [MW] \equiv generator\ i\ power\ output\ constraints$$

$$L(t)\ [MW] \equiv load\ (demand)\ on\ power\ system$$

The total production cost of a system per hour ($C_{prod}$), the objective function to be minimized, is the sum of the product each generator’s fuel cost with its power output. The decision variables can be grouped in a column vector $x$ that represents the power output of each generator in the system, while the parameters within c represent each generator’s cost of generation. Different generators, such as steam plants that run on coal or natural gas, cost different amounts to operate because of different fuel costs. The total amount paid by the load called the ‘cost to load’ ($C_{load}$), is the market price ($P_m$) of electricity times the total load ($L$).

*Equation 4-2*

$$C_{prod} = c^T x$$

*Equation 4-3*

$$C_{load} = P_m * L$$

*Equation 4-4*

$$P_{total} = C_{load} - C_{prod}$$

$$Where \ldots$$

$$c\ [\$/MWh] \equiv marginal\ cost\ of\ generation\ column\ vector$$

$$C_{load} \equiv total\ cost\ to\ load\ [\$/h], P_{total} \equiv total\ profits$$

$$P_m \equiv market\ price\ [\$/MW],\ L \equiv total\ load\ [MW/h]$$

The profits from providing electricity accrue to specific generators based on rules defined by the independent system operator but are generally defined by Equation 4-5, Equation 4-6, Equation 4-7. The simple scenarios in Appendix II illustrate system optimization and generator compensation. Note, fuel-based generators in the simulation had an additional variable operating cost that was included. More details on this can be found in Section 4.6.1 .

*Equation 4-5*

$$C_n = x_n * c_n$$

*Equation 4-6*

$$R_n = x_n * P_m$$

*Equation 4-7*

$$P_n = R_n - C_n$$

$$Where \ldots$$

$$C_n \equiv cost\ of\ generator\ n\ [\$/h]$$

$$R_n \equiv revenue\ of\ generator\ n\ [\$/h]$$

$$P_n \equiv profit\ of\ generator\ n\ [\$/h]$$

## 4.2 Software Tools

Plexos, a commercial power system simulation software made by EnergyExemplar, is used to aid in the power system simulation (solving the optimization problem described in 4.1 ). An academic Plexos license was acquired directly from the developer to conduct this study. A Plexos 'Short Term' model with a 24-hour look-ahead[4] was used alongside a 'Medium Term' model[5]. A toolkit, called the 'Plexos Toolkit'[6], was developed to combine the tabular data from six publically available datasets (**Figure 4-1**) and define power system models for simulation in Plexos. The toolkit consists of two modules: PlexosDBGenerator (**Figure 4-2**), which generates a power system representation for Plexos, and PlexosResults, which processes solution files and generates graphics after the Plexos simulation.

[4] Plexos dispatches generators to minimize cost of operation over the course of one day- and consequently solves an entire year in 365 such steps.

[5] The Medium Term model decomposes long term constraints (such as annual energy use for pumped storage) into smaller constraints for the Short Term model to further optimize.

[6] Written in the Python Programming Language

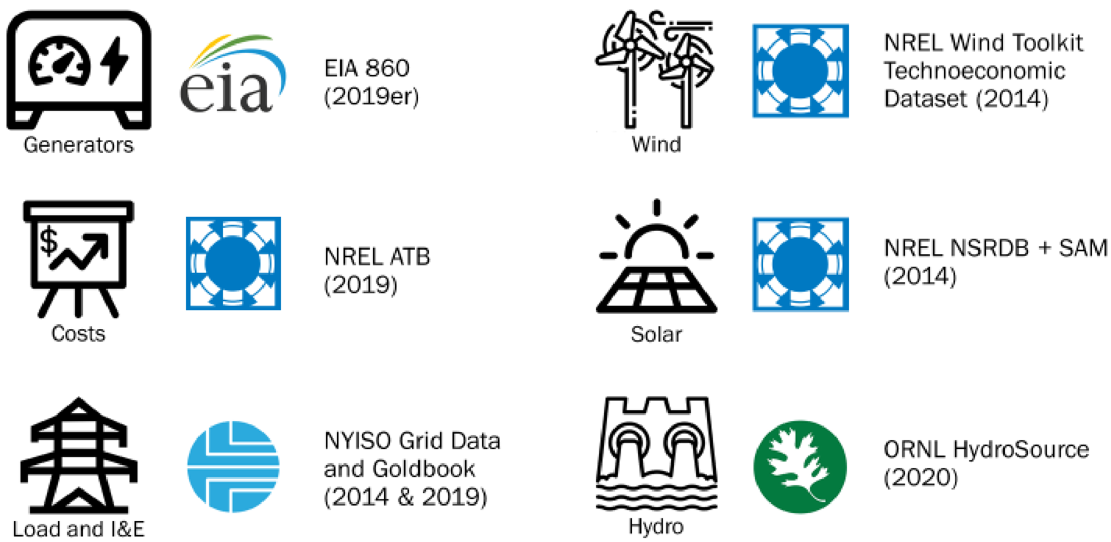


*Figure 4-1: Dataset Summary.*

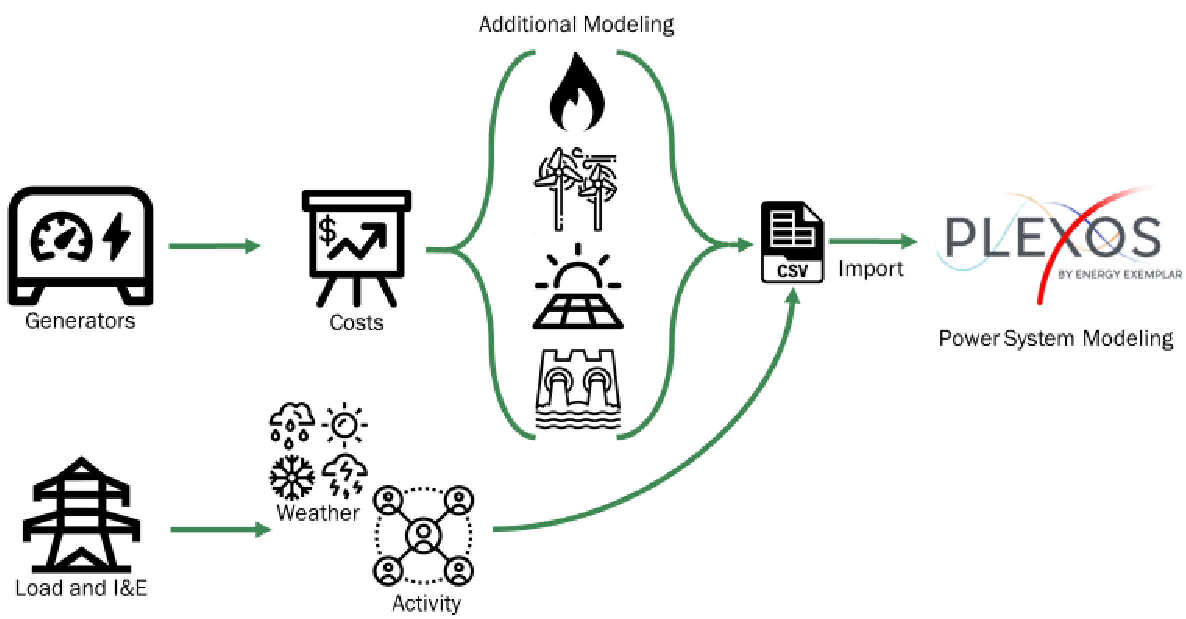


*Figure 4-2: System Diagram for Plexos Toolkit's PlexosDBGenerator Module.*

## 4.3 Topology

A regional New York's power system was constructed with a two-nodes: one node for upstate and one for downstate to capture basic intrastate dynamics. Consistent with the way NYISO definitions, the upstate region contained NYISO regions A-E while the downstate node included F-K (Figure 3-7). For the 2019 model, a 4050 [MW] transmission line links the two nodes; the power limit was selected based on modeling results from NYISO Operating Study Summer 2019 [27]. The transmission capacity was increased for the 2040 and 2050 models (**Table 5-5**). **Table 4-1** was used to group individual NYISO interface flows to the regions.

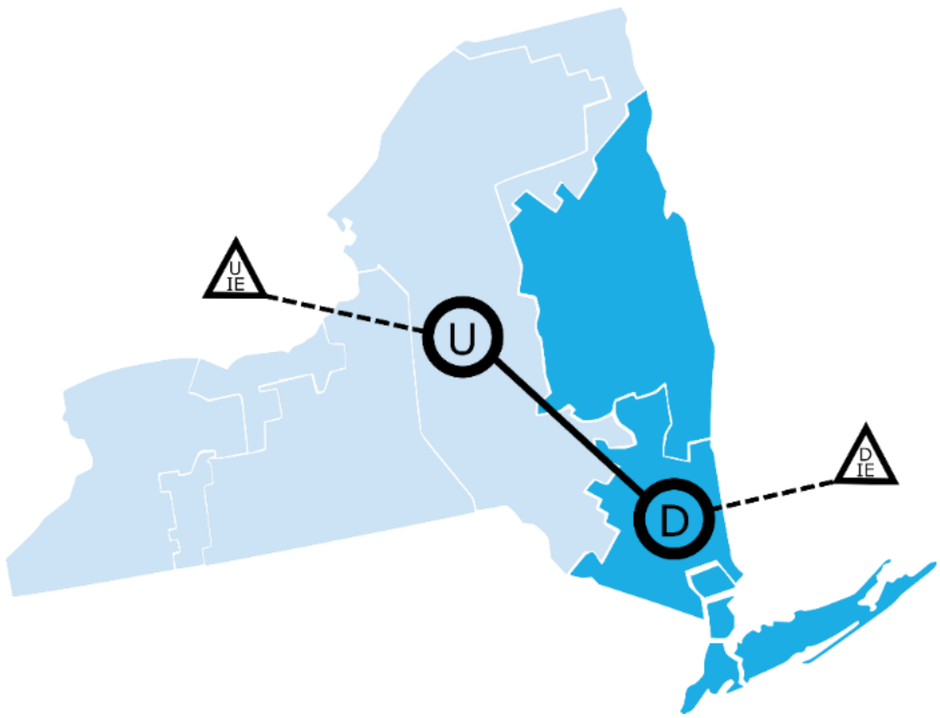


***Figure 4-3: Two-node Model.*** *Note: An upstate and downstate region were defined identically to NYISO's definition.*

***Table 4-1: External Interface Flow Mapping to Regions.*** *Note: The interface flows were aggregated into upstate and downstate Import and Exports based on this mapping. Source: NYISO 2018 Power Trends [28] and NYISO Customer Service.*

| Upstate | Downstate |
|---|---|
| HQ Chateauguay | NPX New England |
| HQ Cedars | NPX 1385 Northport (NNC) |
| IESO | NPX Cross Sound Cable (CSC) |
| PJM Keystone | PJM Hudson TP |
| | PJM Neptune |
| | PJM Linden VFT |

## 4.4 Load

Electricity demand is influenced by human activities, seasonal and weather variables (such as temperature). For example, in summer, there tends to be more electrical demand than winter due to electric air conditioning. Also, the hottest few days of the year place a peak demand on the electrical system. The weather also affects the supply of electricity, especially from renewable energy resources which depend on wind and solar radiation. Since load and renewable resource availability is coupled by weather, power system studies with renewable energy resources should use time-synchronous[7] resource and load data. Furthermore, the relationship between demand and renewable resources over time significantly affects the dynamics of a power system. For example, a day with highly variable wind and solar means conventional generation technologies must be operated differently (lots of ramping up and down) from a day in which there is no wind or solar.

The *weather year* is the period during which a power system study will use time-synchronous load and resource data. For this study, the latest resource data available from NREL's Wind Toolkit and National Solar Resource Database (NSRDB) is from 2013. Since it is difficult to collect time-synchronous data over many years, the load and resource data from a single weather year is used repeatedly throughout a multiyear power system study. However, some modification of the load is necessary to capture how it evolves over long periods. Every year, the NYISO releases its prediction for how they expect electrical demand to change. Figure 4-4 shows data from NYISO's 2020 Goldbook [29], which predicts annual energy consumption statewide to decline until 2027 and then increase through 2050.

[7] Time-synchronous data is collected over the same time period. For example, load data from 2013 and solar resource data from 2014 is not time-synchronous.

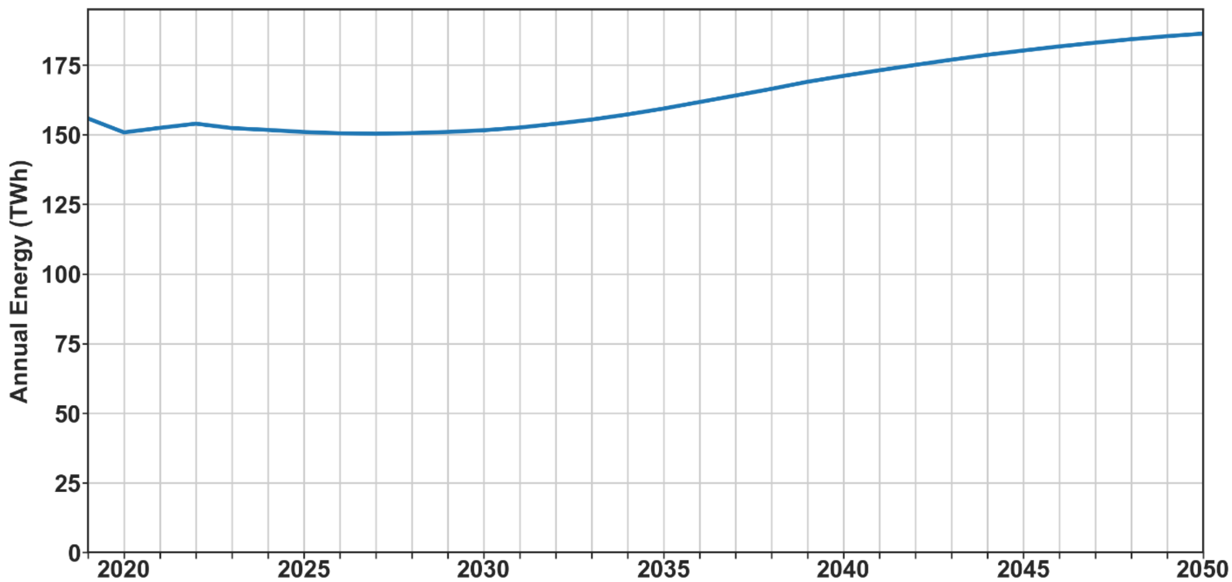


*Figure 4-4: Instate Annual Energy Consumption Growth.* *Source: NYISO 2020 Goldbook [29]*

2019 is the *base year* of the study – the first year of the simulation time horizon. Although actual load data is available from 2019, the time-synchronous resource data from each renewable generator was not available at the time of the study. Consequently, constructing a new load curve for the base year was necessary using the load from the weather year (2013). A scaling factor was used to scale every hour of load in 2013 based on the ratio of the total annual energy consumption between the two years; Appendix IV shows the Python script algorithm that was used to scale the load and related figures in this section. Appendix IV contains a table of the scaling factors applied to the load for each region, which when aggregated form the weather adjusted load statewide, upstate, and downstate load for 2019-2050 (**Figure 4-5**).

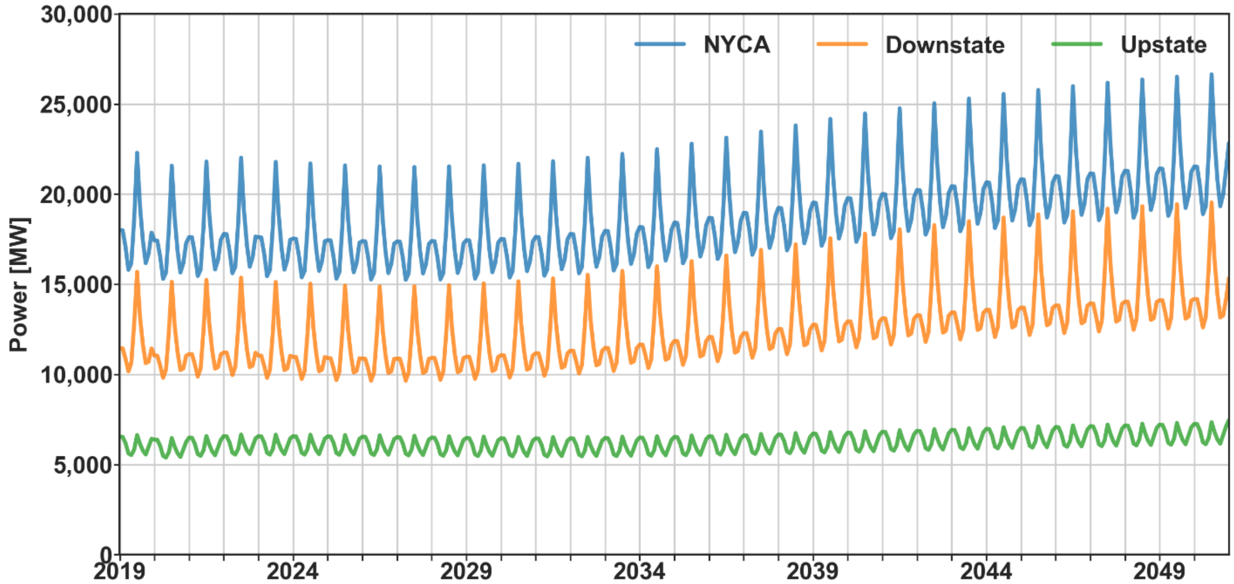


***Figure 4-5: Monthly Average Instate Load (2019-2050).*** *Note: The 2013 load shape was used with a magnitude modified to achieve the NYISO's projected annual energy consumption per year. New York Control Area (NYCA) is the statewide total load. The Downstate and Upstate load curves at an hourly frequency are used in the models.*

**Figure 4-6** shows a snapshot of the scaled load during the peak load month of July; the scaled 2019 load is always lower, which is consistent with the lower energy consumption of 2019 relative to 2013. Effectively, the 2019 scaled load represents what the electrical load would have been if the same weather and human behavior occurred in 2019 as it did in 2013. Even though the new load has a different shape, it makes it possible to study how the infrastructure in place in 2019 would have behaved under the same conditions that occurred in 2013. A key assumption of the study is that the weather and human behavior in the future will not be significantly different from what it was in 2013; a study that is focused on analyzing power system resiliency might consider the operational effects of different weather or human activities on the power system.

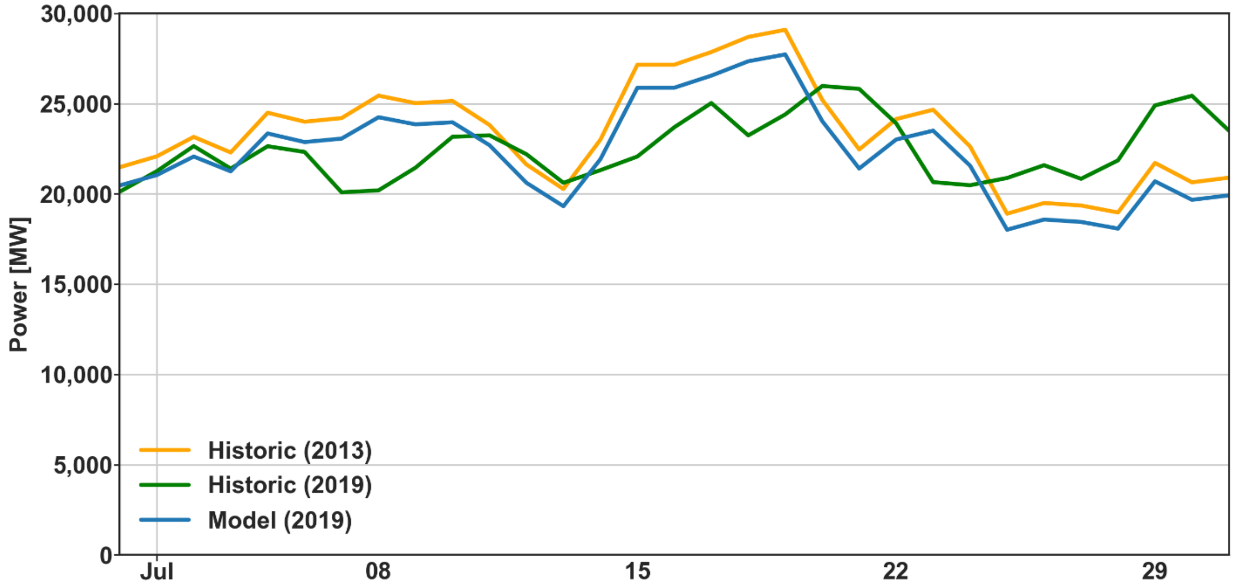


***Figure 4-6: Modeled Load from Weather Year (July 2013) and Base Year (July 2019).*** *The 2019 Scaled load essentially represents what the electrical load would have been had the same weather and human activity from 2013 occurred in 2019.*

## 4.5 Imports and Exports

The NYISO region benefits itself and its neighboring regions by exchanging power. To model imports and exports, a similar methodology to the load model was used. For the upstate and downstate region, the shape of the 2013 net import time series was used for each year of the study, but the magnitude was modified for each year to maintain the ratio of annual energy consumed to annual imports for the upstate and downstate region. **Figure 4-7** shows the daily average imports and exports in the two regions relative to load, and **Table 4-2** shows how the ratio of energies was calculated.

To model imports and exports for 2019 and the future, it was assumed that the energy ratio for each region would remain constant. The ratios together with regional energy consumption projections from the NYISO Goldbook, plotted in Figure 4-4, the 2013 time series shape was scaled each year to create a net import series for 2019-2050 at an hourly frequency; **Figure 4-8** plots the daily average values. The upstate region sees higher imports than the downstate region, and at certain hours may be a net exporter of energy – but not as often as downstate.

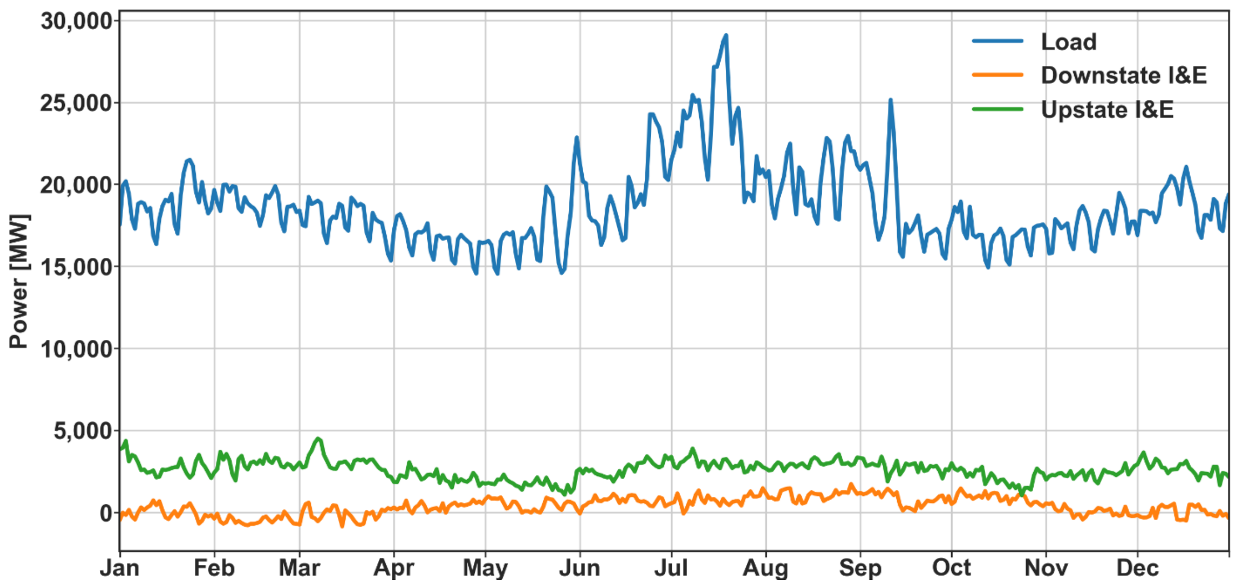


***Figure 4-7: Daily Average Imports and Load (New York 2013).*** *Source: NYISO resampled at a daily frequency.*

***Table 4-2: Ratio of Annual Imported Energy to Load (2013).*** *Note: Load and Imports in [TWh].*

| Region | Load | Imports | Imports: Load |
|---|---|---|---|
| *Upstate* | 56.89 | 22.70 | 0.40 |
| *Downstate* | 106.62 | 3.26 | 0.03 |

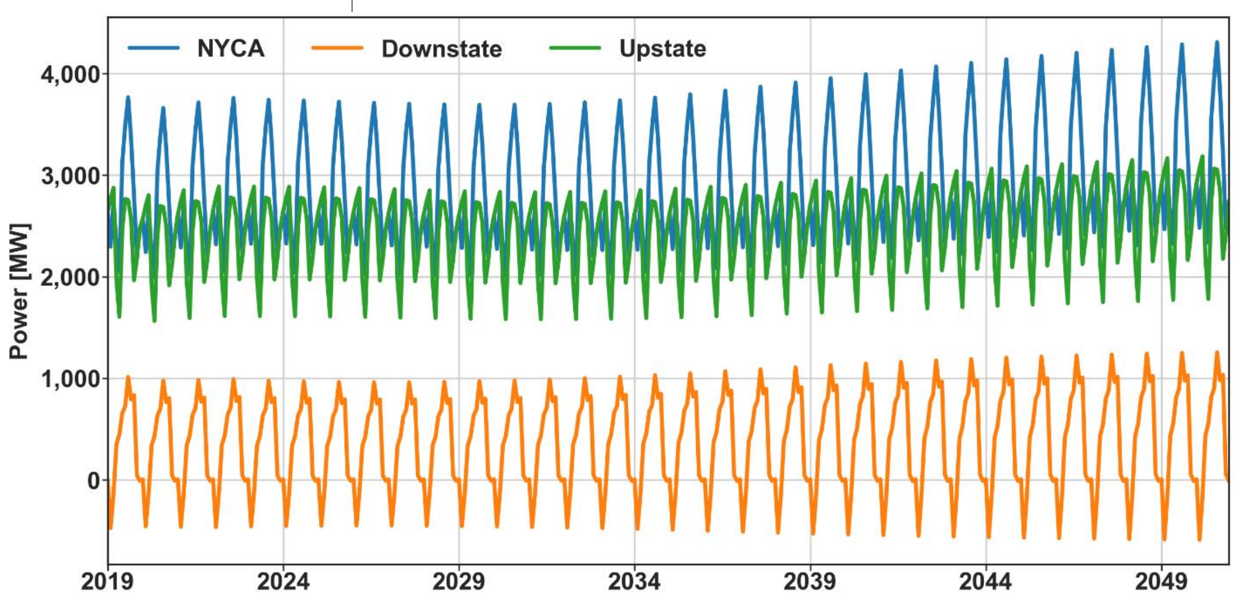


***Figure 4-8: Monthly Average Upstate and Downstate Import and Exports (2019-2050).*** *Note: Hourly data was used in the model. Source: Annual Energies from NYISO's Goldbook [29].*

## 4.6 Generators

The EIA860 database contains generator parameters for generators above 1 [MW] in nameplate capacity. About 1400 generators resided within NY's geographic boundaries in the 2019 early release version of the EIA860 database[8]. Key parameters specified in the database include location, technology, fuel, nameplate capacity, summer nameplate capacity, and minimum stable level (MSL) – which is the minimum load the generator can operate at. To model each generator in the study, cost parameters based on technology had to be acquired by mapping the EIA860 technologies to those in NREL's Annual Technology Baseline (ATB). The ATB includes parameters (and projections for them through 2050) that are crucial for simulating their operation in a wholesale market – mainly the bid price for each generator. **Figure 4-9** shows a high-level view of the installed capacity and operation in 2019 that will be modeled.

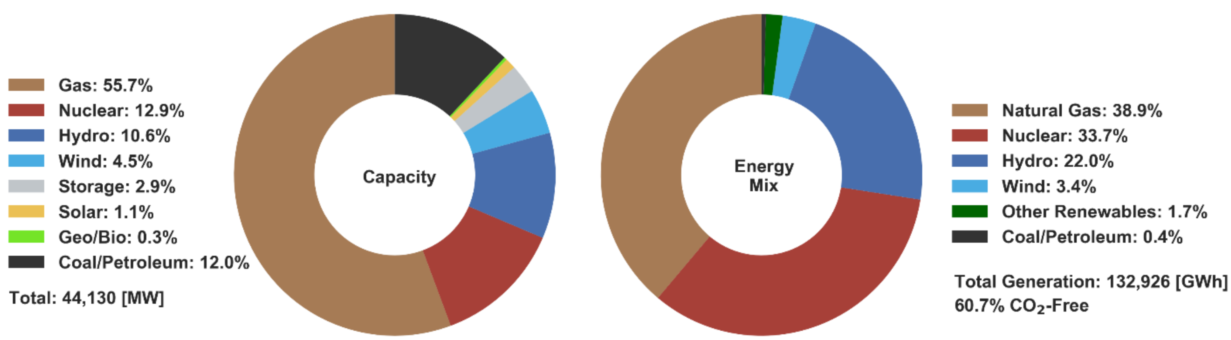


***Figure 4-9: Instate Energy Mix and Capacity (2019).*** *Sources: NYISO Data for Energy Mix and EIA860 for Capacity. Note: In the energy mix, hydro includes pumped storage, while other renewables category includes solar, storage, methane, refuse, and wood. There were no geothermal power plants in New York in 2019.*

While the EIA860 database was used to specify the generators in the 2019 model, additional information was needed to specify the generators for the 2050 model, discussed in Chapter 5 . Results from NREL's Standard Scenario study, which includes a capacity expansion model, was used to specify the installed generator capacities for the 2050 model. **Figure 4-10** shows how the

[8] There were no offshore wind turbines installed in New York in 2019.

installed capacity changes over time in New York from NREL's study, while **Table 4-3** shows the breakdown of capacity by technology from the Standard Scenarios study. Capacity is how much power a generator can provide at a given moment; similarly, storage capacity is how much power can be output from storage – which is different from battery duration measured in (kWh).

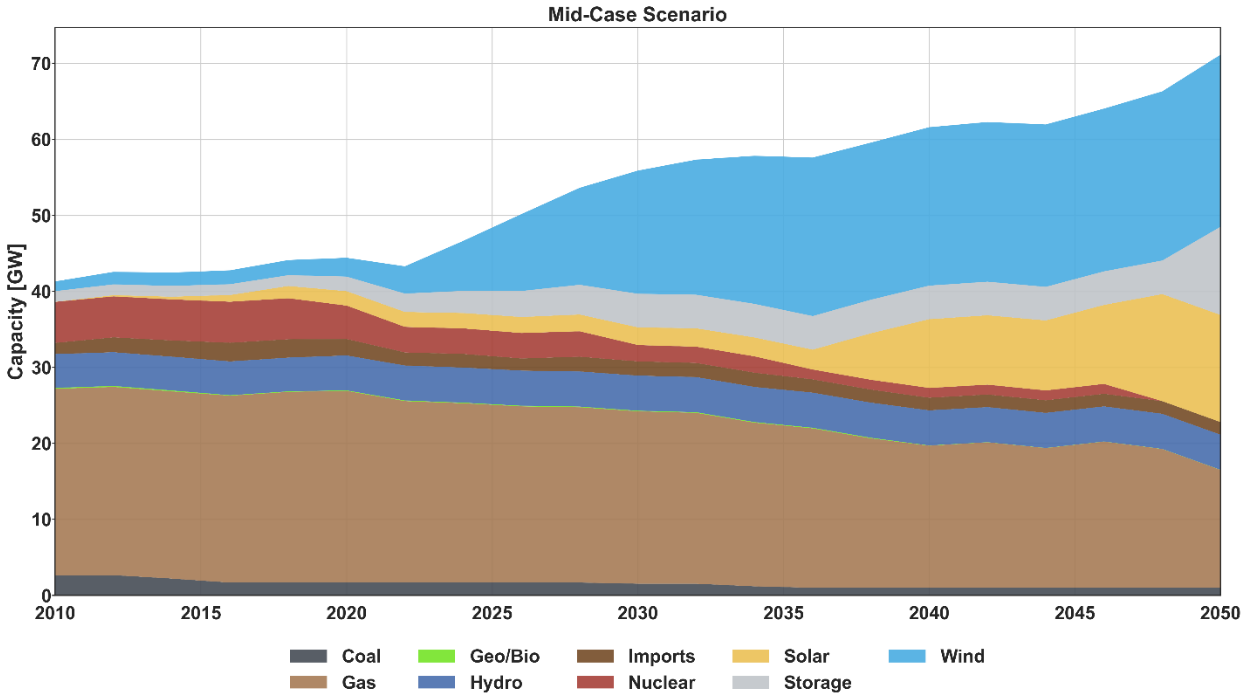


***Figure 4-10: Standard Scenario Capacity Evolution (Mid-Case Cost Scenario, New York).*** *Source: NREL Standard Scenarios 2019 [2].*

**Table 4-4** shows the installed capacities by fuel type for 2050 from the Standard Scenarios and the constructed model for NY. The discrepancy between the installed capacity from the NREL study and New York exists because different capacity increments of each technology were assumed; for example, according to the ATB database, the representative utility-scale facility is 23 [MW].

*Table 4-3: **Summary of NREL Standard Scenario 2050 Results.** Note: The capacity results from here were used to construct the 2050 model.*

| Technology | Capacity [MW] | Generation (TWh) |
|---|---|---|
| *Land-Based Wind* | 13,630 | 55.69 |
| *Offshore Wind* | 9,000 | 34.24 |
| *NG-CC* | 12,066 | 26.55 |
| *NG-CT* | 1,968 | - |
| *Storage* | 11,622 | (2.49) |
| *Utility PV* | 11,089 | 19.30 |
| *Rooftop PV* | 3,005 | 4.09 |
| *Hydro* | 4,615 | 25.38 |
| *Imports* | 1,654 | 12.68 |
| *Oil-Gas-Steam* | 1,464 | 0.49 |
| *Coal* | 1,021 | 3.91 |
| *Biopower* | 19 | - |
| *CSP* | - | - |
| *Geothermal* | - | - |
| *Nuclear* | - | - |

### 4.6.1 Fuel-based

To use critical modeling parameters from the ATB, the generators technologies contained in the EIA860 database were mapped to ATB technologies (Table 4-4). In the absence of direct mapping, one was made based on the closest heat rate from the EIA860's average heat rates by the prime mover and energy source Appendix VI [30].

*Table 4-4: **Technology Map Between EIA860 Generators and ATB Technologies for Fuel-based Generators.** Note: The parameters from the mid-case cost scenario were used throughout the study. Any generator technology that could not be mapped directly with this map was mapped using the nearest heat rate from (Appendix VI).*

| EIA 860 Technology | ATB Technology |
|---|---|
| Natural Gas Steam Turbine | Gas-CC-AvgCF |
| Natural Gas Fired Combined Cycle | Gas-CC-AvgCF |
| Natural Gas Fired Combustion Turbine | Gas-CT-AvgCF |
| Natural Gas Internal Combustion Engine | Gas-CC-AvgCF |
| Other Natural Gas | Gas-CC-AvgCF |
| Nuclear | Nuclear |
| Petroleum Liquids | Gas-CT-AvgCF |
| Conventional Steam Coal | Coal-new-AvgCF |
| Municipal Solid Waste | Biopower-Dedicated |
| Landfill Gas | Biopower-Dedicated |
| Wood/Wood Waste Biomass | Biopower-Dedicated |
| Other Waste Biomass | Biopower-Dedicated |

A generator's technology type affects its cost of generating electricity – some of the most critical parameters include fuel cost, heat rate, and variable operation and maintenance (VO&M) expense. The marginal (incremental) cost of generation – called the short-range marginal cost (SRMC) – for each generator technology is used in production cost models to model how generators would be dispatched to economically meet demand – called economic dispatch. Equation 4-8 describes how SRMC is calculated, while **Table 4-5** shows the SMRC for each ATB technology in the database; renewable technologies have zero SRMC because the 'fuel' is free and they only have fixed operational and maintenance costs (independent of how much energy is produced by the generator).

***Equation 4-8: Short Run Marginal Cost (SMRC) Formula.***

$$SRMC\left[\frac{\$}{MWh}\right] = Fuel\ Cost\left[\frac{\$}{MMBtu}\right] * Marginal\ Heat\ Rate\left[\frac{Btu}{kWh}\right] * \frac{1}{1000} + VO\&M\ Charge\ [\frac{\$}{MWh}]$$

***Table 4-5: SMRC of Fuel-based ATB Technologies (Mid Case Cost Scenario)****. Note: Storage and renewable energy technologies have zero SMRC. Dollar amounts are for 2019 but expressed in 2017 dollars.*

| ATB Technology | Year | Fuel Costs [$/MMBtu] | Heat Rate [Btu/kWh] | VO&M [$/MWh] | SMRC [$/MWh] |
|---|---|---|---|---|---|
| *Nuclear* | 2019 | 0.6 | 10.5 | 2.3 | 2.3 |
| *Coal-new-AvgCF* | 2019 | 2.0 | 8,790.0 | 5.0 | 23.0 |
| *Gas-CC-AvgCF* | 2019 | 3.2 | 6,420.8 | 2.77 | 20.5 |
| *Gas-CT-AvgCF* | 2019 | 3.2 | 9,695.8 | 7.14 | 38.2 |
| *Biomass-Dedicated* | 2019 | 3.1 | 13,500.0 | 5.6 | 46.9 |

At a minimum, a generator owner would offer to sell electricity into a wholesale energy market at a 'bid price' that is equal to their generator's SRMC – otherwise, they would lose money[9]. Wholesale markets are designed so that generators compete with low bid prices so that they get dispatched and receive the market overall marginal cost of generation (See 3.3.1 Energy Market for an example). A production cost model simulates the wholesale market based on the assumption the bid prices would be very close to a generator's SRMC.

---

[9] Some plants, like nuclear power plants have other costs which might make it economically beneficial to bid lower than their SMRC to make sure they are selected to run – this dynamic is outside the scope of the study.

Table 4-6 shows an example of all the parameters specified for a fuel-based generator. The winter and summer nameplate capacities from the EIA860 database were used to define a pattern for the rating property. In the absence of a specified minimum output in the EIA860 database – zero was assumed for the minimum stable level. Each generator was attached to the upstate or downstate node depending on what county the generator was in according to the EIA860 database and the regional map (**Figure 4-3**). Datafiles containing annual values for heat rate, fuel price, and VO&M were created from the ATB and used so that generators still in existence in 2050 could use updated values.

***Table 4-6: Example of Generator Properties Specified for a Gas-CC-AvgCF Generator in 2019.*** *Note: Generator ID: 4043. The parenthesis next to the properties contains the months the property applies to, while the values next to the datafiles represent a snapshot 2019 values used. Emissions were modeled using fuel and emission objects in Plexos.*

| Property | Value | Units |
|---|---|---|
| *Units* | 1 | - |
| *Rating (M1-4,10-12)* | 164.2 | MW |
| *Rating (M5-9)* | 169.7 | MW |
| *Minimum Stable Level* | 115 | MW |
| *Heat Rate* | Datafile (6420.8) | Btu/kWh |
| *Fuel Price* | Datafile (2.77) | $/MMBtu |
| *VO&M Charge* | Datafile (3.2) | $/MWh |
| *Emissions (CO2, Hg, NOx, SO2)* | 117; 0; 0.02; 0.0033 | lb/MMBtu |

Four greenhouse gases (provided by the ATB) were modeled for each generator technology including sulfur dioxide, nitrogen oxides, mercury, and carbon dioxide. The modeling results focus on quantifying the amount of carbon dioxide because it is by far the largest source that contributes to climate change. The other gases gave significantly smaller warming potentials but may have important impacts on air quality that were not analyzed in this study.

*Table 4-7: Greenhouse Gas Emissions [lbs/MMBtu] from operation by ATB Technology. Note: Nuclear and all other generators had no emissions. Includes all fuel-based technologies with emissions, even those that were not installed in 2019 according to the 2019 EIA860 database.*

| ATB Technology | $SO_2$ | $NO_X$ | HG | $CO_2$ |
|---|---|---|---|---|
| *Coal-new-AvgCF* | 0.1 | 0.08 | 4.36E-06 | 210.55 |
| *Biomass-Cofirenew* | 0.1 | 0.08 | 4.36E-06 | 210.55 |
| *Gas-CT-AvgCF* | 0.0098 | 0.15 | 0 | 117 |
| *Gas-CC-AvgCF* | 0.0033 | 0.02 | 0 | 117 |
| *Biomass-Dedicated* | 0.08 | 0 | 0 | 0 |

In 2050, the capacity of each fuel-based generator technology is predicted to be less than the amount installed in 2019 according to the Standard Scenario results. Consequently, to model the individual generators present in the 2050 system, only the most recently installed generators for each generator technology were included. An ordered list for each technology was created and summed top-down until the cumulative capacity equaled close to 2050 amount prescribed by the Standard Scenario results.

### 4.6.2 Wind

In contrast to fuel-based generator technologies, regional weather differences cause significant differences in the performance of wind turbines. Consequently, modeling regional and temporal variation of wind power is necessary for a study focusing on the integration of renewable energy sources. A cost curve[10] methodology was used to determine the locations of wind turbine sites. Based on the assumption that owners of generation would seek to minimize their costs and therefore increase their profit, locations with the lowest LCOE were assumed to be installed before those with higher LCOE. It was also assumed that capacity factor alone could be used to assign LCOEs values to a particular generator when in practice LCOE is affected by other parameters as well (3.4.2 Cost Comparison).

[10] Also called a supply curve.

Unlike the other generators in the study, the wind resource was modeled on a site basis instead of a generator basis due to the nature of data available from NREL's Wind Toolkit. The Wind Toolkit Power Production Dataset includes over 100,000 (1 [TW] in total capacity) existing, planned, and speculative sites for onshore and offshore wind turbines for the contiguous United States. The dataset was created to generate simulated wind plant output and forecasts. Sites are available on a 2x2 [km] spatial resolution, which can fit up to eight 2 [MW] wind turbines, and development capacity of up to 16 [MW][11]. The theoretical power production profile of 100m hub height wind turbines are available at a 5-min temporal resolution.[12] For more information about this dataset see the dataset's technical documentation [31].

About 3,400 wind sites were included for consideration in the New York study. All the onshore sites within the borders of New York State were included as well as 531 offshore sites in bodies of water close to New York State borders[13]. Figure 4-11 plots the location of each wind site considered in the study. Each site is color-coded by the technical resource group[14] determined by mapping each site's capacity factor to the closest capacity factor for each technical resource group (TRG) in NREL's 2019 Annual Technology Baseline (ATB) using the mid-case cost scenario [26]. See Table VII-1 for a table mapping these values, which were then used to assign LCOE's to each site from the ATB database.

The same 3,200 sites from Figure 4-11 can be plotted on a cost curve like the one in Figure 4-12 using the ATB mapping between technical resource group and levelized cost of energy.

[11] Class 1 offshore wind turbines were assumed.

[12] The 5-min power data was resampled in 1 hour intervals using the average value. Consequently, the 'start' of the hour datetime convention was used for the wind power resource.

[13] It is possible that some of the offshore site selected currently belong to/will be developed to serve regions other than New York.

[14] A technical resource group is a turbine performance classification.

Onshore wind sites are cheaper to develop than offshore sites because they do not require expensive underwater foundations. Sites with lower technical resource group are higher performing, meaning that they generate more energy than other sites and diffuse the cost of the turbine over more units of energy. The cost curve's x-axis shows that over 40,000 [GW] of wind capacity could be theoretically installed in New York.

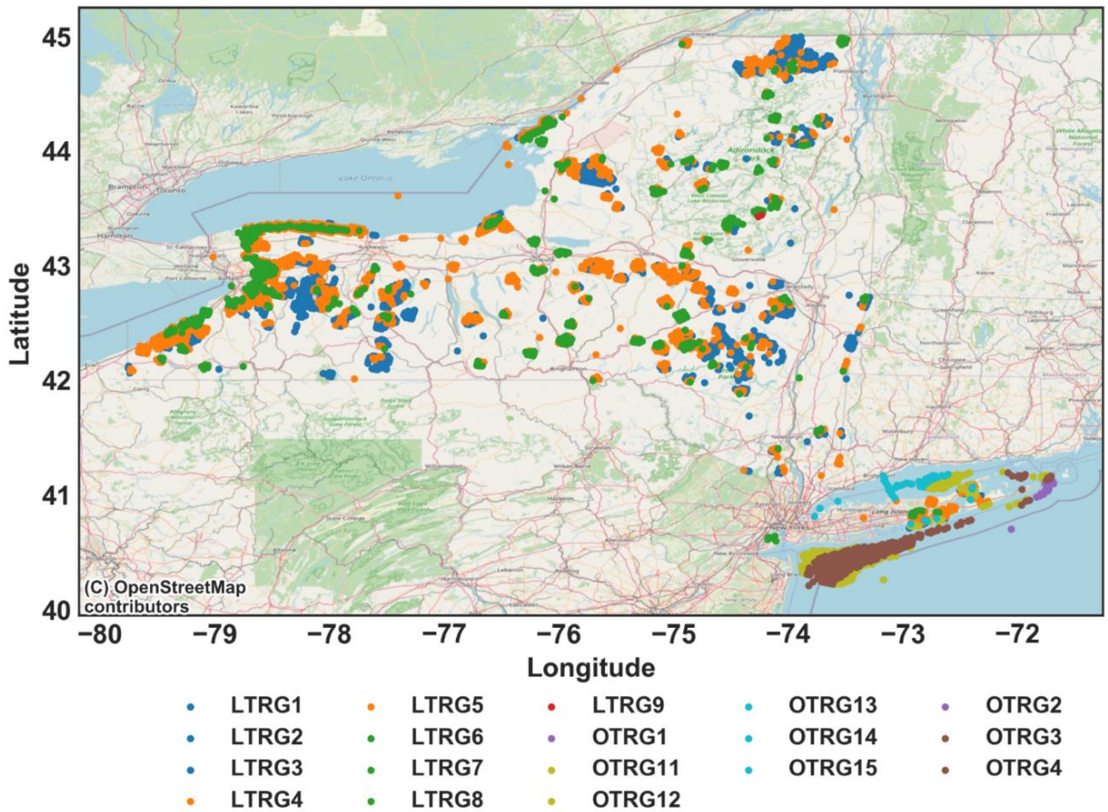


***Figure 4-11: Wind Sites in NY State by 2019 Technical Resource Group.*** *Note: Includes both developed and undeveloped sites. Onshore within NY State borders included and offshore sites near NY were selected manually; in practice, some of the offshore sites may be developed for use in neighboring regions. Source: NREL Wind Toolkit Power Production Dataset [31].*

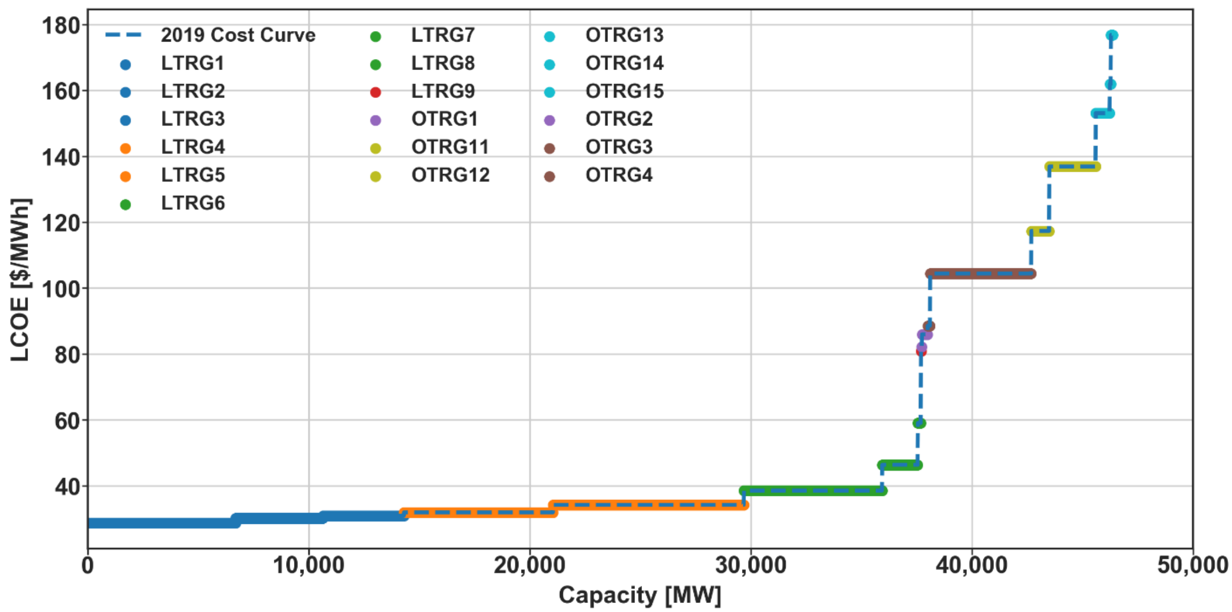


***Figure 4-12: Wind Energy Cost Curve (NY 2019).*** *Note: The x-axis shows cumulative capacity. This figure shows the statewide cost curve, but one was used for each NY county to determine which sites were assumed to be installed in 2019.*

The sites in Figure 4-11 and Figure 4-12 include both developed and undeveloped sites, and a necessary first step was to determine which sites were assumed to be installed in 2019. According to the 2019 EIA 860 database, there was 1986 [MW] of total installed summer wind capacity in the state. To determine which Wind Toolkit sites were to be deemed 'installed' in 2019, a cost curve like Figure 4-12 was created for each NY county, and sites were assumed installed starting from the lowest LCOE[15] until the sum of all the site capacities roughly equaled the total sum of installed nameplate capacity in a county according to the EIA database. There were no offshore wind turbines installed in 2019, so none of the ones from the dataset were included for 2019.

To construct the wind capacity for 2050, the Standard Scenario's stated that there was 13,630 [MW] onshore and 9,000 [MW] offshore wind installed (**Table 4-3**). The sum of all offshore wind from the dataset was 8,656 [MW] and was included, and the onshore wind was

[15] Since the mapping of wind sites to LCOE's was made based on capacity factor, its equivalent to say that sites with higher capacity factors were assumed to be installed before those with lower capacity factors.

increased to 13,974 [MW] to make the total wind capacity was in the NY model as close to the aggregate Standard Scenario number as possible. Wind Turbines have a technical life of about 30 years, and it was assumed that any wind sites whose generators were ready for decommissioning would be replaced instead of abandoning the site and building somewhere new.

### 4.6.3 Solar

The hourly power curve for each solar power plant in the EIA860 database was modeled using NREL's System Advisor Model (SAM). SAM is a free techno-economic software model that facilitates decision-making for people in the renewable energy industry [32]. The solar resource data from the weather year (2013) was acquired from NREL's National Solar Radiation Database (NSRDB) and used to simulate the hourly power output from each EIA generator. Since there was a relatively small cumulative nameplate capacity installed (474 [MW]) in 2019[16], and a supply curve approach was not feasible under the time constraints, resource data for just two locations was used to model the solar generators. Depending on its location, each solar generator used resource information from the NSRDB sites specified in **Table 4-8**.

***Table 4-8: Geographic Locations for Solar Resource Modeling.*** *Source: NREL NSRDB [33].*

| Region | Latitude | Longitude | Altitude | Station Id |
|---|---|---|---|---|
| *Upstate* | 42.13 | -78.84 | 569 | 1094459 |
| *Downstate* | 42.89 | -78.66 | 209 | 1096346 |

For each solar generator in the EIA860 database, the nameplate capacity was used in SAM with several other assumed parameters summarized in **Table 4-9**. The SAM program produced an hourly time series that was linked to the 'Rating' property for each generator in Plexos, the power system simulation software used to conduct the study (**Table 4-10**).

[16] The goal is to model how the solar generators in existence in 2019 would have behaved under 2013 weather conditions.

***Table 4-9: Parameters Specified in SAM to Generate Power Curves.*** *Note: 42-degree tilt was used for the upstate generator and 43-degrees was used for solar generators in the downstate region. For the tilt, it is common practice to use the latitude degree – for upstate, it was set to 42 and for downstate, it was set at 43.*

| DC to AC Ratio | Inverter Efficiency [%] | Array Type | Tilt [°] | Total System Losses [%] |
|---|---|---|---|---|
| 1.2 | 96 | 1-axis tracking | 42 or 43 | 14.05 |

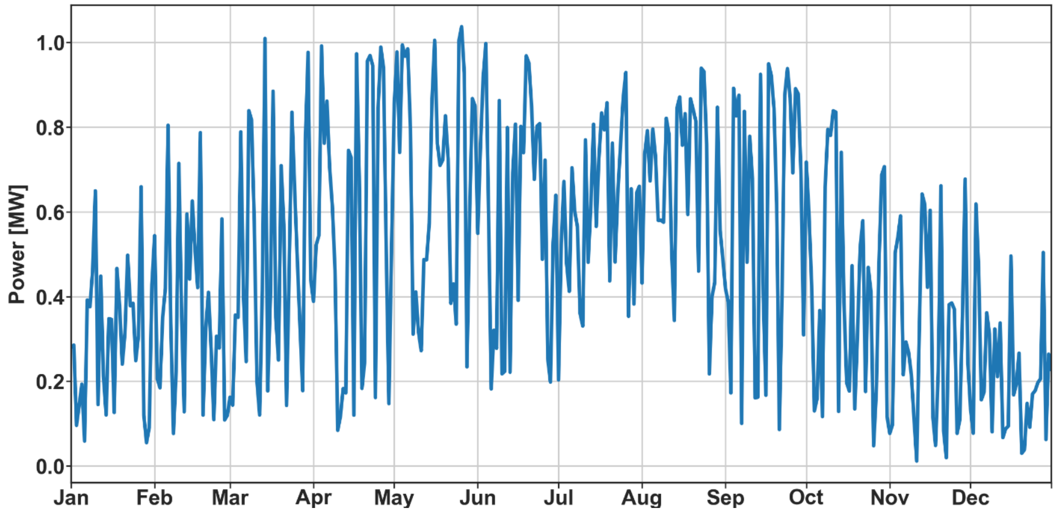


***Figure 4-13: Daily Average Solar Output of EIA860 Photovoltaic Generator 18013 from SAM (2013).*** *Note: The frequency of the time series used in the Plexos simulation was hourly.*

The nameplate capacity from the EIA860 database was used to set the maximum capacity property in Plexos, but because the Rating property effectively overrides this parameter for the study. Since the EIA860 database did not specify a minimum stable level for any solar generators it was assumed to be zero. As for the wind generators, fuel costs and VO&M charges were also assumed to be zero. The hourly time series from SAM, depicted as a daily average in **Figure 4-13**, was linked to the rating property in Plexos.

***Table 4-10: Example of Generator Properties Specified for a Photovoltaic Generator (2019).*** *Note: The rating property in Plexos allows for passing a time series of power output. Generator ID: 18013.*

| Property | Value | Units |
|---|---|---|
| *Rating* | Datafile (Timeseries) | MW |
| *VO&M Charge* | 0 | $/MWh |
| *Fuel Costs* | 0 | $/MMBtu |

To model the solar generators for the 2050 system, the total capacity of residential and utility-scale PV of 14,094 [MW] from the Standard Scenarios was used (**Table 4-3**). Since a dataset containing candidate solar sites was not readily available like it was for wind, a generic generator candidate had to be constructed. According to the ATB, the representative size of a utility-scale solar PV plant in the US is 23 [MW], so it was selected as the incremental size of each additional site. Subtracting out the installed capacity in 2019 from the total available in 2050 provided the remaining available installed capacity. The available capacity was assumed to be distributed evenly between the downstate and upstate regions, which when divided by the representative size plant resulted in 296 units in each region for a total of 592 (**Table 4-11**). The same time series from the locations specified in **Table 4-9** were linked to the rating property in Plexos.

***Table 4-11: Solar Photovoltaic Generators for Downstate Region in 2050.*** *Note: An identical set of properties is set for the candidate generators in the downstate region.*

| Property | Value | Unit |
|---|---|---|
| *Units* | 296 | - |
| *Rating* | Datafile | MW |
| *Fuel Price* | 0 | $/MMBtu |
| *VO&M Charge* | 0 | $/MWh |

### 4.6.4 Hydropower

Hourly resource data was not readily available for hydropower generators, so a different modeling approach was used from the other renewable energy resources. The Oak Ridge National Laboratory's HydroSource dataset was used to define the maximum annual energy (**Table 4-12**) use for each hydropower plant in the EIA database [34]. The summer and winter nameplate capacities from the EIA860 database were used to define the rating properties to capture some variation in how much water is available during different times of the year[17]; though most of the generators had identical capacities all year round. The minimum stable level was defined for each generator based on what was specified for the minimum capacity in the EIA860 database. As a

[17] In absence of a winter or summer nameplate capacity in the EIA860 database, the nameplate capacity was used.

renewable resource, the VO&M Charge and Fuel Costs were assumed to be zero throughout the study.

***Table 4-12: Example of Generator Properties Specified for an Existing Hydroelectric Generator (2019).*** *Plant ID 10712.*

| Property | Value | Unit |
|---|---|---|
| *Rating (m5-9)* | 0.2 | MW |
| *Rating (m1-4, 10-12)* | 0.1 | MW |
| *Minimum Stable Level* | 0.1 | MW |
| *Max Energy Year* | 11 | GWh |
| *VO&M Charge* | 0 | $/MWh |
| *Fuel Price* | 0 | $/MMBtu |

The same generators installed in 2019 were assumed to continue to be in operation in 2050 because the stated 2050 capacity from the Standard Scenario results was approximately equal to the total installed capacity in 2019 from the EIA860 database. This is also consistent with the fact that hydropower generators often have very long technical lives and most of the large capacity in New York has already been harnessed.

## 4.7 Storage

Hydropower pumped storage and battery storage were the only two utility-scale storage technologies included in the NY model[18]. When modeling the battery storage capacity in 2050 using NREL's Standard Scenario results, it was assumed that the existing pumped hydro storage facilities were maintained from 2019, while the existing battery storage was retired, and new battery storage was installed. The pumped hydro capacity in 2019 and 2050 was 1,240 [MW], while battery capacity in 2019 and 2050 was 33 [MW] and 10,382 [MW] respectively. In 2050, a total of 11,622 [MW] of storage was included as specified by the Standard Scenario results (**Figure**

[18] Flywheels were not included in the model.

**5-1**), which is significantly higher than the state's 3,000 [MW] storage mandate by 2030 (**Table 5-1**).

### 4.7.1 Pumped Storage Hydropower

All pumped storage was modeled in Plexos using a generator between a head and a tail reservoir. The nameplate capacity from the EIA860 database was used as the maximum capacity of the generator, while the gross annual energy generation from the HydroSource database determined the maximum volume of the tail and head storage. Since the annual energy was provided and not the actual energy capacity of each plant, it was assumed at the start of the simulation, the tail storage was set to be 100% full and the head storage 0%. This approach was different than the one taken from battery storage due to the nature of the data available through the HydroSource database. To model pumped storage in 2050, it was assumed that the same pumped storage facilities that exist in 2019 remain in existence in 2050 because pumped storage can only be implemented in certain geographies. The total pumped storage capacity installed in both the 2019 and 2050 model was 1,240 [MW].

***Table 4-13: Example of Properties Specified for Pumped Hydro Storage (2019).*** *Note: At the start of the simulation head storages are empty and tail storage is 100% full. Plant ID: 4306.*

| Property | Value | Unit |
|---|---|---|
| *Rating* | 1000 | MW |
| *Min Stable Level* | 4 | MW |
| *Pump Efficiency* | 70 | % |
| *Pump Load* | 1000 | MW |
| *Max Volume* | Head: 508, Tail: 508 | MWh |
| *Initial Volume* | Head: 0, Tail: 508 | MWh |
| *End Effects Method* | Auto | |
| *VO&M Charge* | 0 | $/MWh |
| *Fuel Price* | 0 | $/MWh |

### 4.7.2 Battery Storage

In 2019, there were only 33 [MW] of utility-scale battery storage installed in New York according to the EIA860 database. In a grid with high penetrations of renewable energy, battery storage is expected to be an important energy arbitrage role - charging when demand is low and there is cheap energy from renewables and discharging when there is peak demand and expensive electricity. To model the batteries in both the 2019 and 2050 model, it was assumed that all batteries could provide four hours of storage at a round trip efficiency of 85% (same assumption as NREL ATB) and with an initial charge of 50%. Lastly, for the batteries installed in 2019, the nameplate capacity from the EIA860 database defined the Max Power property. **Table 4-14** provides an example of how a battery was modeled in Plexos.

***Table 4-14: Example of Properties Specified for Downstate Battery*** *(2019). Note: Batteries were assumed to be four-hour batteries able to operate at their max power for four hours. SoC – State of Charge.*

| Property | Value | Unit |
|---|---|---|
| *Units* | 1 | - |
| *Capacity* | 20 | MWh |
| *Max Power* | 5 | MW |
| *Initial SoC* | 50 | % |
| *Charge Efficiency* | 85 | % |
| *Discharge Efficiency* | 100 | % |

Since batteries have an expected lifetime of only about 15 years, the existing batteries in place in 2019 were assumed to be retired by 2050. New batteries were added to both the upstate and downstate regions equally at increments of 10 [MW] and 40 [MWh]. **Table 4-14** shows an example of properties defined for all the downstate batteries. 519 units were assumed to be installed in the downstate region, which when combined with the same amount in the upstate region total 10,380 [MW] and 41,520 [MWh] of installed battery storage in the state.

***4-15: Example of Properties Specified for Downstate Batteries (2050).*** *Note: Batteries were assumed to be four-hour batteries able to operate at their max power for four hours.*

| Property | Value | Unit |
|---|---|---|
| *Units* | 519 | - |
| *Capacity* | 40 | MWh |
| *Max Power* | 10 | MW |
| *Initial SoC* | 50 | % |
| *Charge Efficiency* | 85 | % |
| *Discharge Efficiency* | 100 | % |

# Chapter 5 Results

## 5.1 Model Validation

To validate the modeling methodology, a necessary first step was to compare the modeled system operation to historic operation. Model validation focused on analyzing generator operation on annual and daily timescales. The production cost model for the 2019 power system was constructed with generator capacities summarized in **Table 5-1**. **Table 5-2** contains the annual dispatched energy from the hourly production cost model – which is visualized in **Figure 5-1**.

The annually aggregate results from the 2019 model were similar to the historical operation, but there were discrepancies for several reasons: The first important consideration is that the model describes how the power system infrastructure in place in 2019 would have operated under the economic activity and weather of 2013[19]. Most likely, the increased wind energy present in the model is most likely due to the fact the Wind Toolkit uses state of the art wind turbines relative to the existing fleet. The significant amounts of wind energy in the model could also be due to better wind resource in 2013 than in 2019, or it could be due to an optimistic site selection methodology[20]. Furthermore, there was notably less solar generation in the model compared to the historic operation which could be due to lower solar resources available in 2013, and/or too conservative of a solar modeling methodology[21]. Lastly, differences in generation categorization between NYISO and the model could be causing a misleading discrepancy. The dispatch of generators on the daily timescale was also similar to historic 2019 operation compared in **Figure**

[19] See Sections 4.6.2 and 4.6.3
[20] See Section 4.6.2
[21] See Section 4.6.3

**5-2** and **Figure 5-3**. There are differences, and this is because the model is simulated under weather and activity patterns of 2013.

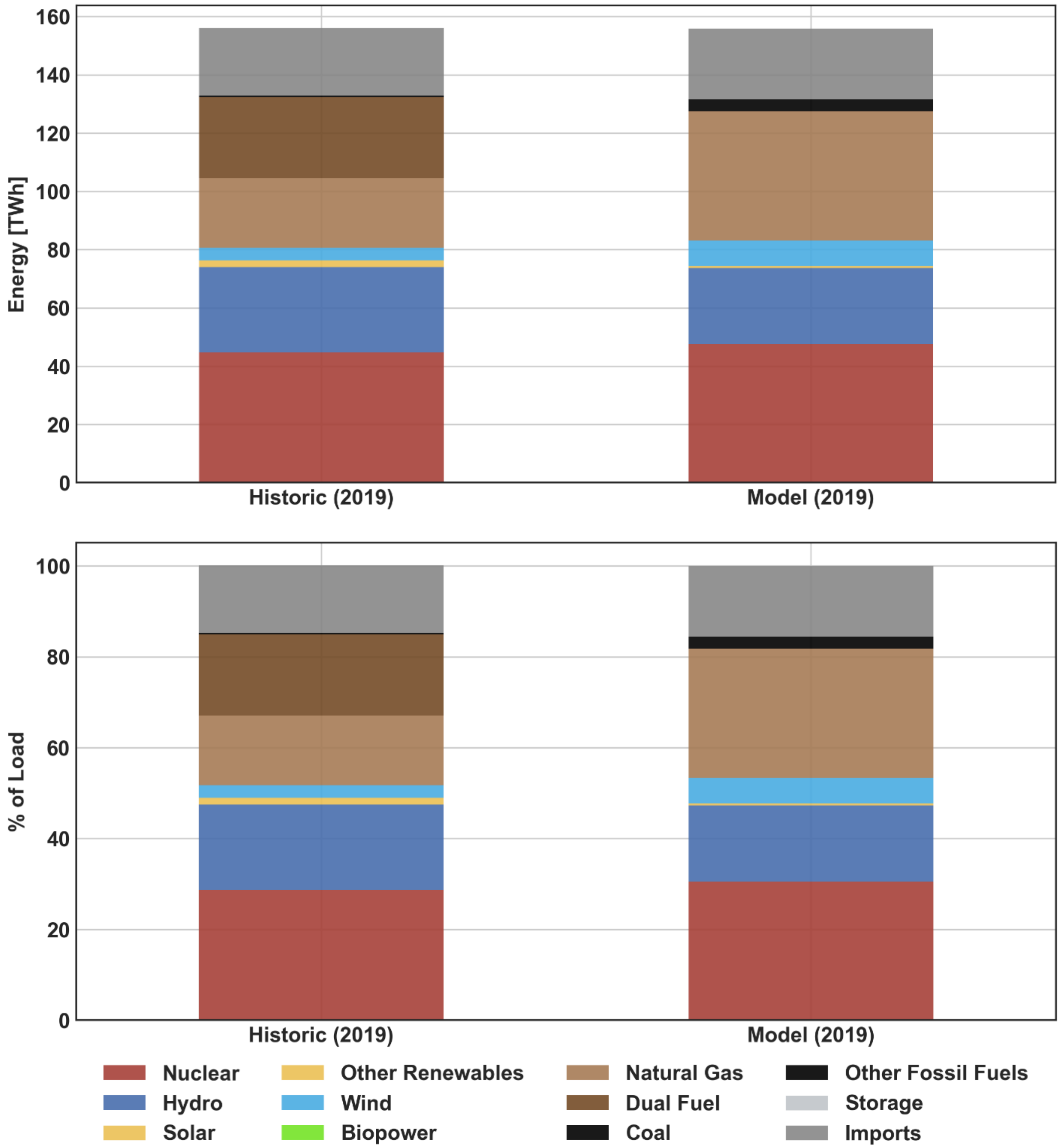


***Figure 5-1: Historic and Modeled Annual Energy Generation.*** *Note: The 'Other Renewables', 'Other Fossil Fuels', and 'Dual Fuel' categories refer exclusively to NYISO Historic data. The NYISO's 'Other Renewables' category contains solar, battery storage, and other generation – unlike the models, which separate storage, solar, and biopower in separate categories. Storage in the 2019 model is so minimal it cannot be seen. Source for Historic Data: NYISO OASIS [35].*

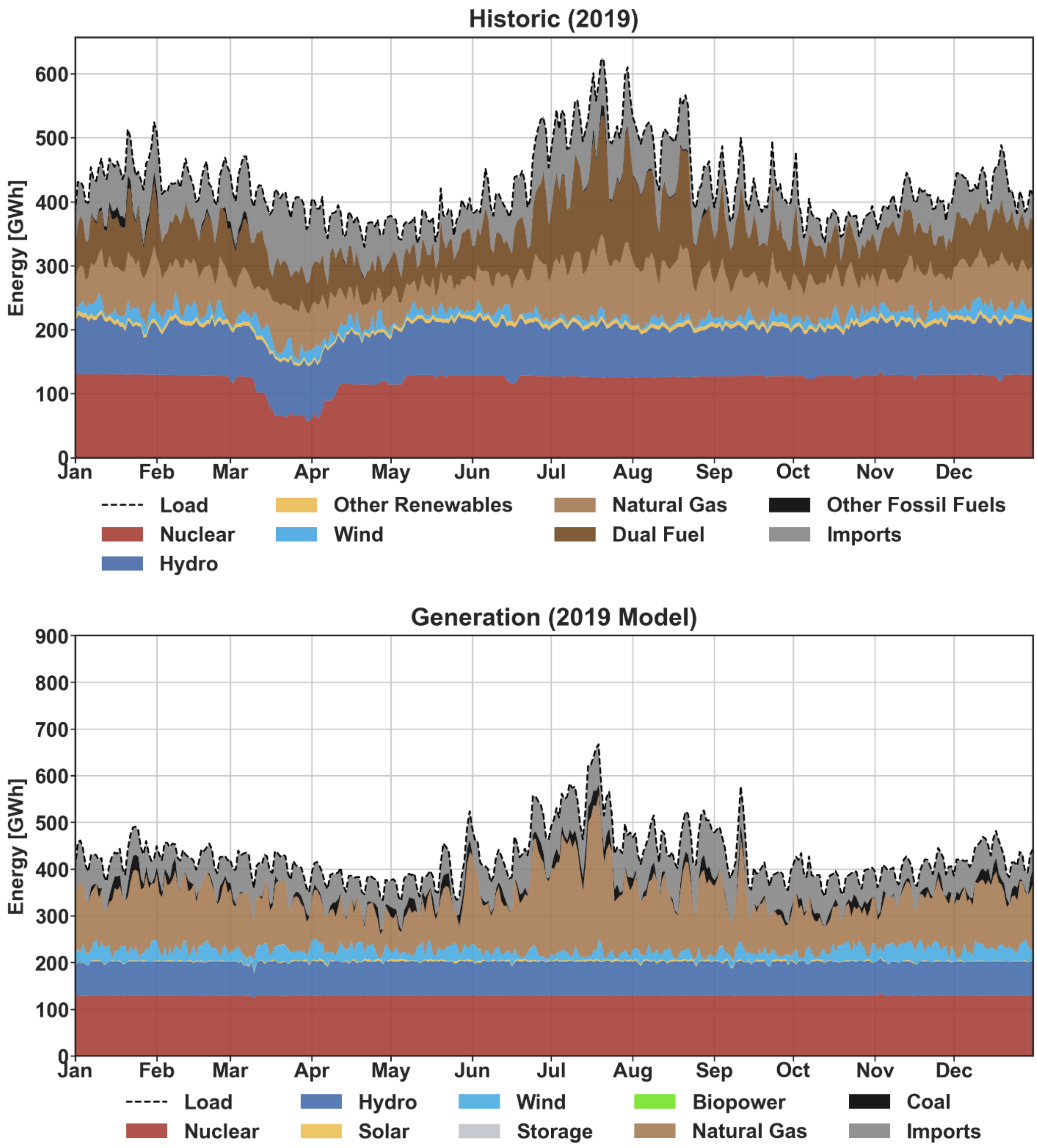


***Figure 5-2: Historic and Modeled Daily Energy Generation (New York State 2019).*** *Note: The simulation occurred on an hourly basis, but the values plotted in the figure represent the aggregate daily energy. The model represents the operation under the weather and economic activity patterns of 2013 but the total annual energies are the same– see 4.4 Load for more details. Source for Historic Data: NYISO OASIS [35].*

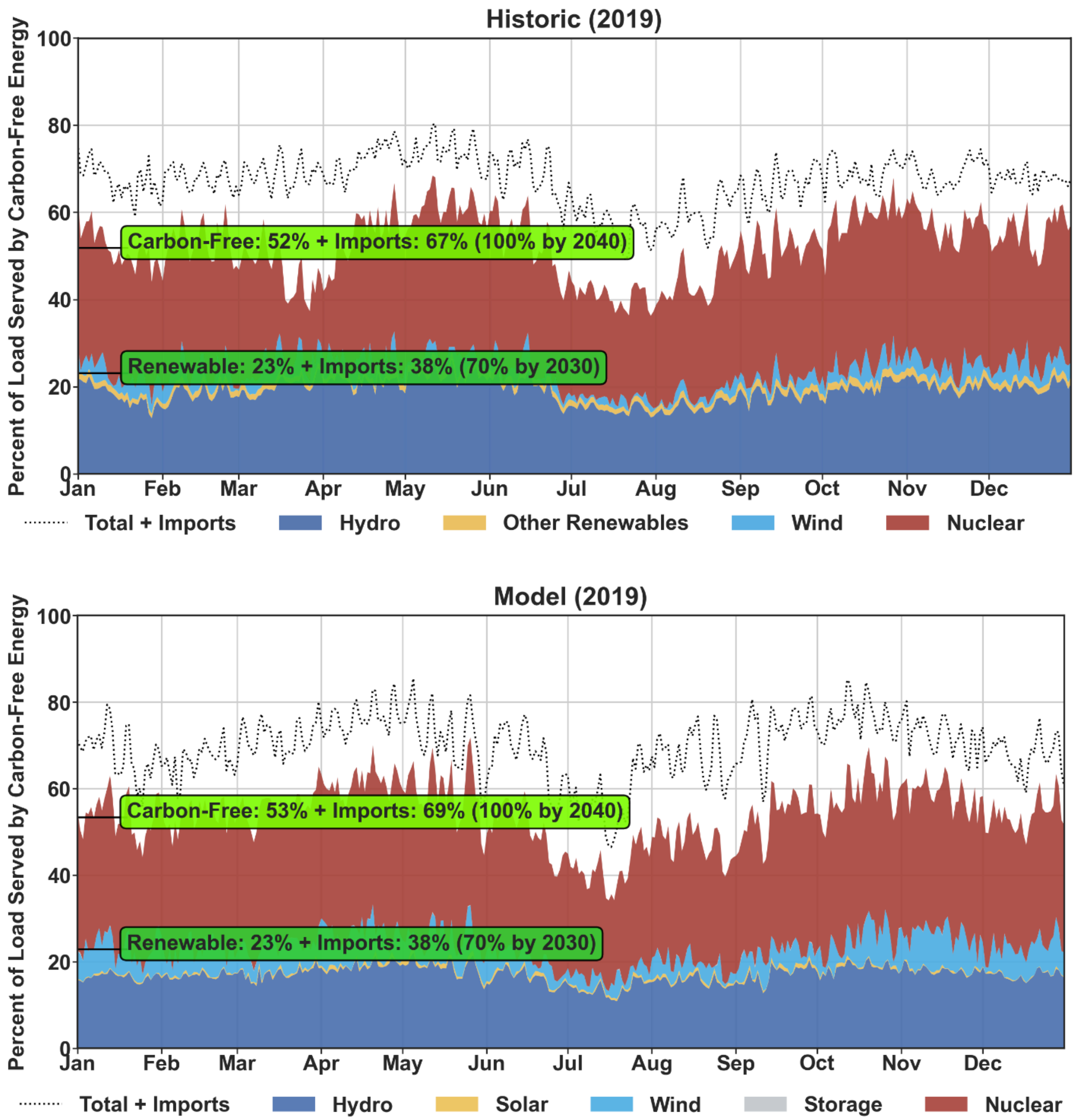


***Figure 5-3: Historic and Modeled Daily Carbon-Free Generation (New York State 2019).*** *Note: The dotted line shows the level of carbon-free energy which served load if all the imported energy procured by utilities from out of state came from carbon-free sources; this information was not immediately available for in 2019. Although NY imports significant amounts of hydropower from Canada not all imports from other regions come from carbon-free sources. Figure inspired by NYISO Power Trends 2020 [28]. Source for Historic Data: NYISO OASIS [35].*

A notable difference in **Figure 5-2** is the reduction in nuclear power beginning in March - which was likely planned maintenance at one of the plants. Although modeling maintenance events were outside the scope of the current study, more detailed models could include such events. Daily hydropower seemed slightly more variable historically compared to the model but overall seemed to accurately capture the daily energy production. Wind production is notably higher and solar is noticeably lower in the model than it was historically in 2019 (**Figure 5-1**). Dual fuel generators were modeled as natural gas generators in the model, and the aggregate operation, providing 'peaking capacity' seems similar enough in **Figure 5-2**.

**Figure 5-3** compares the carbon-free operation of the power system between the model and reality to visualize the progress toward achieving the power sector goals outlined by the Climate Leadership and Community Protection Act. The act specifies "No later than [June 13, 2021], the commission shall establish a program to require that: (A) A minimum of [70%] of the statewide electric generation secured by jurisdictional load-serving entities to meet the electrical energy requirements of all end-use customers in New York State in [2030] shall be generated by renewable energy systems; (B) and that by [2040] the statewide electrical demand system will be zero-emissions " [36]. Since the requirement applies to load-serving entities (utilities), the measure of carbon-free and renewable generation comes with a paired measurement that includes imports. Since utilities can procure power from out of state from renewable or carbon-free sources, the second figure gives an idea of what the numbers would be if all imports were procured from renewable or carbon-free sources. As can be seen, New York is far from achieving the ambitious goals of the CLCPA in 2019, and the model reflects similar performance toward achieving those results as seen in **Figure 5-3** and **Table 5-2**.

## 5.2 Model Comparison

With some confidence that the modeling methodology is valid, the next step was to study how the power system might operate differently in the future. Since building a capacity expansion model was outside the scope of the project, future power system configurations specified by two pieces of literature were studied. The first study called ‘The Global Relevance of New York’s Power Sector Targets’ [37] was conducted by McKinsey and Company was focused specifically on New York. In contrast, the second power system configuration came from NREL’s Standard Scenario study[22] which is a model built for the entire country. The goal was to construct models with the specified amount of generation capacity for each technology and study the technical feasibility of achieving the goals of the CLCPA.

### 5.2.1 Capacity

Three models were constructed in the study: one for the existing 2019 system, one for 2040 based on the McKinsey study, and one for 2050 based on the NREL study. **Table 5-1** summarizes the total capacities configured for each generator technology. For more on the modeling methodology refer to section 4.6 . The 2040 McKinsey Model notably specified significantly higher amounts of renewable energy capacity (wind, solar, hydro) than the 2050 NREL Model specified. For solar, it specifies nearly double the 14 [GW] of solar capacity specified in the NREL model. A significant difference between the two future models is that the NREL model did not include nuclear as part of the energy mix, however, it was ultimately included in the 2050 model after it was found that the system could not meet demand without it[23]. Furthermore, the McKinsey model specifies 21.8 [GW] of natural gas-fueled generators compared to NREL’s 15.4 [GW]. The NREL model has significantly more storage however with about 11.6 [GW] compared to McKinsey’s 5 [GW]. All battery storage in the 2040 and 2050 models were assumed to be capable of delivering power for eight hours, while the 2019 model only had four-hour storage capability.

[22] NREL’s Standard Scenarios report does mention that aggregated results (both geographic and temporal) should be emphasized over narrowly filtered results.

[23] It was the first thing that was adjusted to keep the rest of the configuration the same.

It is important to note that models for 2040 and 2050 are not meant to be interpreted as occurring chronologically.

***Table 5-1: Comparison of Historic and Model Installed Capacities by Technology [MW].*** *Sources: EIA860 [30], McKinsey [37], NREL Standard Scenarios [2] .*

| **Technology** | **2019 Historic**[24] | **2019 NY Model** | **2040 McKinsey Model** | **2040 NY Model** | **2050 NREL Model** | **2050 NY Model** |
|---|---|---|---|---|---|---|
| *Hydro* | 4,692 | 4,682 | 5,800 | 5,786[25] | 4,615 | 4,682 |
| *Wind* | 1,991 | 1,987[26] | 27,500 | 27,510[27] | 22,630 | 22,630[28] |
| *Solar*[29] | 474 | 474 | 28,800 | 28,810 | 14,094 | 14,090 |
| *Nuclear* | 5,709 | 5,709 | 3,300 | 3,154 | -[30] | 5,709[31] |
| *Gas* | 24,565 | 28,003[32] | 21,700 | 21,815[33] | 15,494 | 16,011[34] |
| *Coal* | 1,415 | 1,415 | 700 | 993 | 1,021 | 993 |
| *Biopower* | 128 | 560 | -[35] | - | 19 | 19 |
| *Storage*[36] | 1,293 | 1,273[37] | 5,000 | 5,000[38] | 11,622 | 11,622[39] |
| *Other* | 3,862[40] | - | 3,200[41] | - | - | - |
| ***Total*** | 44,130 | 44,102 | 96,000 | 93,068 | 64,880 | 75,756 |

[24] Nameplate Capacities were used from the EIA860 database [30]

[25] Includes the hydro generators installed in 2019 (EIA860 DB) and 1104 [MW] new capacity (See Section 4.6.4 )

[26] No offshore wind included in 2019 NY Model. All the other models included offshore wind.

[27] Includes 27,510 [MW] onshore and 8,656 [MW] offshore wind.

[28] Includes 13,974 [MW] onshore and 8,656 [MW] offshore wind.

[29] Concentrated Solar (CSP) was not modeled.

[30] The NREL Standard Scenario assume there is no nuclear in New York State in 2050.

[31] The NREL model did not specify any nuclear but running the system without it resulted in unserved energy. After unserved energy was observed again when running with the addition 3,154 [MW] of nuclear (specified by the McKinsey model)– the existing (2019) amount was used - resulting in no unserved energy.

[32] Consists of 20,334 [MW] Gas CC and 7,669 [MW] Gas CT.

[33] 14,899 [MW] of Gas CC and 6,916 [MW] of Gas CT was included.

[34] 12698 [MW] of Gas CC and 3,314 [MW] of Gas CT was included.

[35] The McKinsey report categorized biopower into the ‘Other’ category together with flexible loads and oil.

[36] Storage includes pumped hydro storage and battery storage. Flywheel storage was not modeled.

[37] Includes 33 [MW] of four-hour battery storage, the rest was existing pumped hydro storage (See Sections 4.7.1 and 4.7.2

[38] Includes 3,700 [MW] of 8-hour battery storage, the rest was existing pumped hydro storage (no new facilities modeled).

[39] Includes 10,382 [MW] of 8-hour battery storage, the rest was existing pumped hydro storage (no new facilities modeled).

[40] Petroleum generators in the EIA860 database were mapped to gas generators in the 2019 (See Section 4.6.1 ).

[41] The McKinsey report categorized biopower into the ‘Other’ category together with flexible loads and oil.

## 5.2.2 Energy Mix

For each of the models, the aggregate annual energy production from each technology can be compared both in magnitude and in a normalized form in **Figure 5-4** and **Table 5-2**.

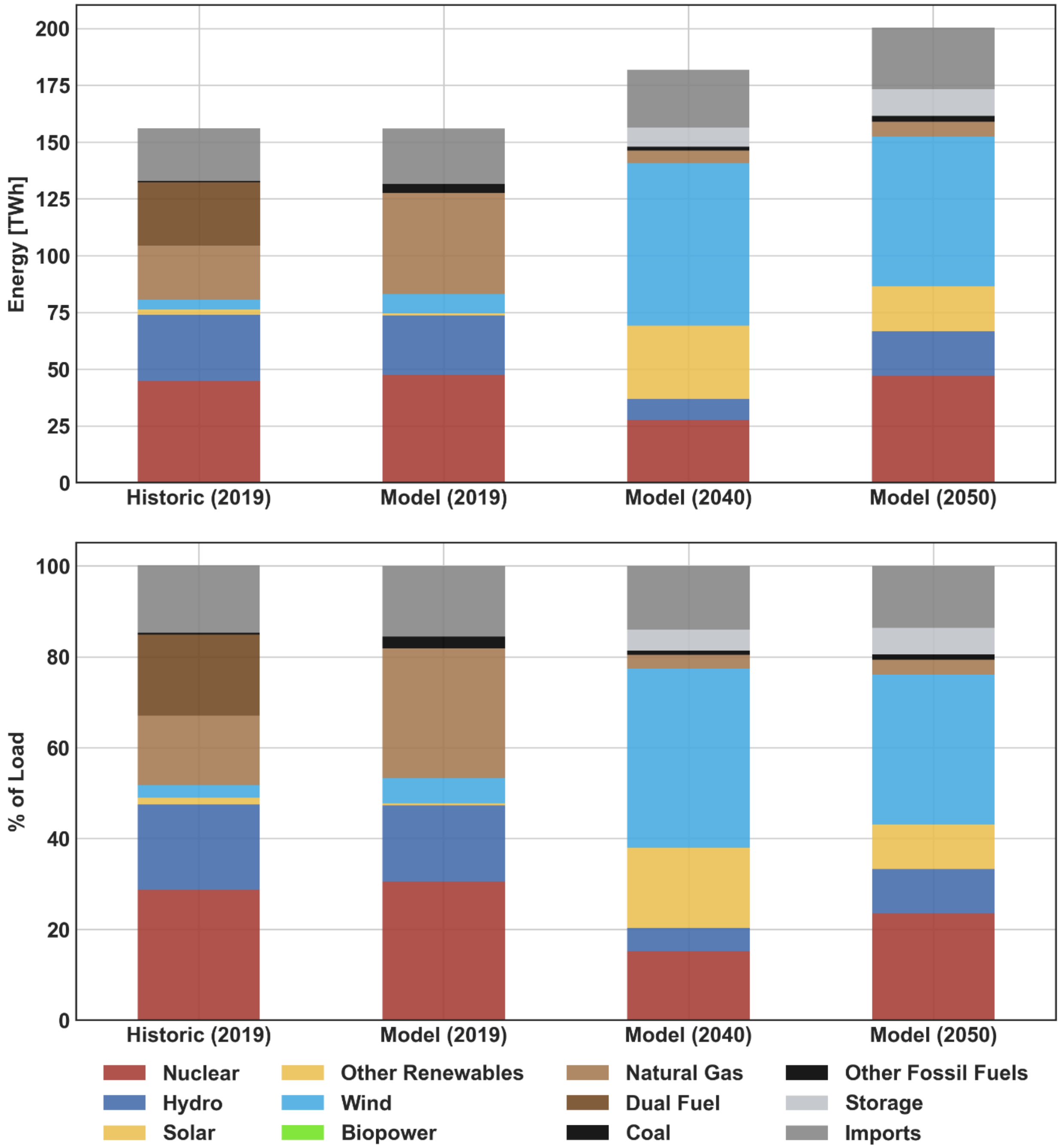


***Figure 5-4: Annual Energy Generation for Historic 2019 and Models of 2019, 2040, and 2050.*** *Note: The 'Other Renewables' and 'Other Fossil Fuels' Categories belong to the color categories from NYISO for the Historic (2019) category.*

***Table 5-2: Annual Energy [TWh] by Technology for Historical 2019 and the Three Models.*** *Note: The historic 2019 categories included energy storage within hydropower and other renewables categories, while the 2019 model separated storage. Storage is included in the 'Total Generation', 'Total Renewable Generation', and 'Total Carbon-Free Generation' categories because it is considered a critical enabling technology for decarbonized power system operation.*

| Technology | Historic (2019) | Historic (2019) [% Of Load] | Model (2019) | Model (2019) [% Of Load] | Model (2040) | Model (2040) [% Of Load] | Model (2050) | Model (2050) [% Of Load] |
|---|---|---|---|---|---|---|---|---|
| *Nuclear* | 44.78 | 29 | 47.46 | 30 | 27.56 | 15 | 47.03 | 23 |
| *Hydro* | 29.24 | 19 | 26.21 | 17 | 9.33 | 5 | 19.63 | 10 |
| *Wind* | 4.47 | 3 | 8.61 | 6 | 71.57 | 39 | 66.01 | 33 |
| *Solar* | - | - | 0.79 | 1 | 32.23 | 18 | 19.76 | 10 |
| *Other Renewables* | 2.21 | 1 | - | - | - | - | - | - |
| *Biopower* | - | - | 0.00 | 0 | - | - | 0.00 | 0 |
| *Natural Gas* | 23.76 | 15 | 44.51 | 29 | 5.61 | 3 | 6.44 | 3 |
| *Dual Fuel* | 27.89 | 18 | - | - | - | - | - | - |
| *Coal* | - | - | 4.00 | 3 | 1.70 | 1 | 2.52 | 1 |
| *Other Fossil Fuels* | 0.57 | 0 | - | - | - | - | - | - |
| *Storage* | - | - | 0.05 | 0 | 8.36 | 5 | 11.76 | 6 |
| ***Total Generation*** | 132.93 | 85 | 131.62 | 84 | 156.35 | 86 | 173.16 | 86 |
| ***Total Renewable Generation*** | 35.92 | 23 | 35.60 | 23 | 121.49 | 67 | 117.17 | 58 |
| ***Total Carbon-Free Generation*** | 80.70 | 52 | 83.06 | 53 | 149.04 | 82 | 164.19 | 82 |
| *Imports* | 23.13 | 15 | 24.29 | 16 | 25.48 | 14 | 27.21 | 14 |
| ***Total Generation + Imports*** | 156.06 | 100 | 155.90 | 100 | 181.83 | 100 | 200.37 | 100 |
| *Load* | 155.83 | 100 | 155.90 | 100 | 181.83 | 100 | 200.37 | 100 |

The first major takeaway is that the models of the future power system take NY from a 53% carbon-free system to about 82% carbon-free. Though a significant improvement, the systems would still fall short of the 100% carbon-free goal by 2040 of the CLCPA. However, if one assumes net imported energy was all carbon-free this number rises to 96%. The models also show that we could move from a power system that is 23% renewable to one that is >58% renewable, though falling short of the renewable energy goal of the CLCPA.

The most notable difference between the 2040 and 2050 models from 2019 is a reduction in the amount of natural gas both in magnitude and as a percentage of the energy that serves load.

In its place, wind becomes the dominant energy source in 2040 and 2050 models – in 2040 it provides 39% of the load in 2040 and 33% of the load in the 2050 model. The models showed that nuclear still has a critical role because initial runs of the 2050 model without any, and with the amount specified in 2040, resulted in unserved energy. Solar energy is the second or third-largest provider of energy in the models after nuclear.

### 5.2.3 Emissions

The driving force behind transitioning the power system is lower emissions. Although carbon budgets do exist, it is hard to say exactly what magnitude of emissions is sustainable for NY's power system. Consequently, the focus will be placed on the relative differences in the emissions from New York's Power sector, which according to NY's Greenhouse Gas Inventory accounted for 13% of the economy-wide emissions of NY State in 2016 (**Table 2-3**). **Figure 5-4** shows the modeled emissions in the context of two historic values. According to the model, the power system in place in 2019 would have produced 37 [MMt of $CO_2$], which is probably overestimating. Nonetheless, the 2040 and 2050 models would have about 18% or 23% respectively of the emissions of the existing 2019 system (**Table 5-3**).

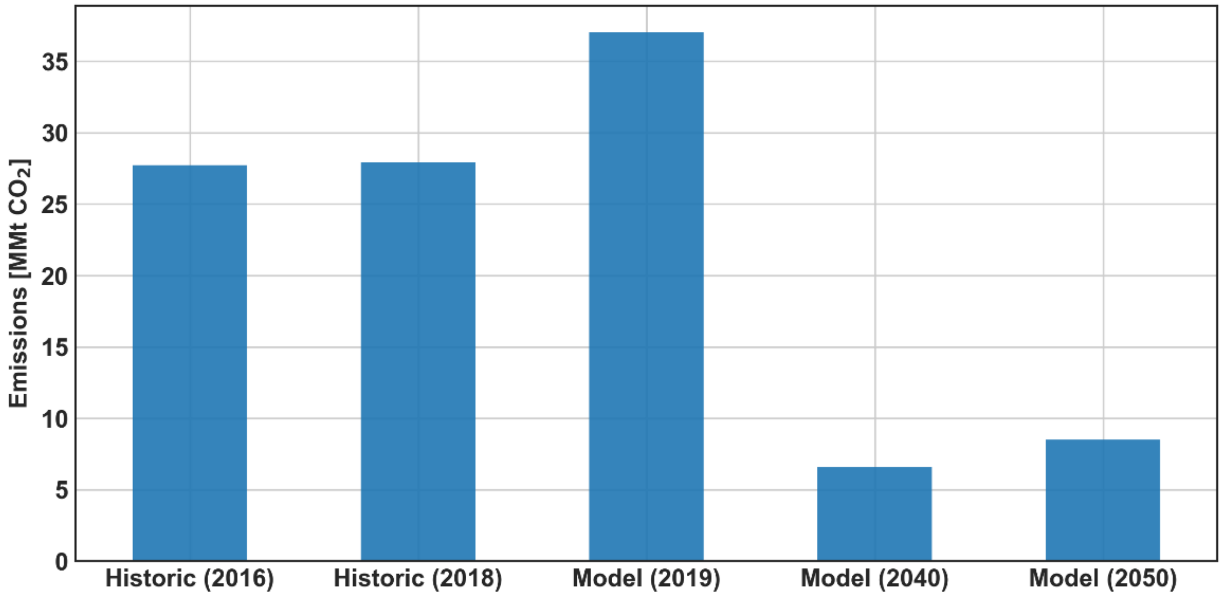


***Figure 5-5: Comparing Model Emissions to Historic Emissions.*** *Note: The historic 2019 emission was not available at the time of this report (projected release by EIA is December 2020). Only the value from Historic (2016) is in carbon-dioxide equivalent units, the remaining values account for carbon-dioxide gas alone. This graphic only includes emissions from in-state generation. Source: Historic 2016 and 2018 are from NYSERDA GHG Inventory [16]and EIA Electricity Profile [38] respectively.*

***Table 5-3: Annual Modeled Emissions [MMt of Gas].*** *Note: This table does not contain gases in carbon dioxide equivalent units -except for Historic (2016) and Historic (2018)., The 2040 and 2050 models show that they would have about 18% or 23% respectively of the emissions of the existing 2019 system (using the 2019 Model results).*

| Gas | Historic (2016) | Historic (2018) | Model (2019) | Model (2040) | Model (2050) |
|---|---|---|---|---|---|
| $CO_2$ | 27.72[42] | 27.93 | 37.04 | 6.57 | 8.51 |
| *Hg* | - | - | 1.39E-07 | 5.87E-08 | 8.73E-07 |
| $NO_x$ | - | - | 7.73E-03 | 1.72E-03 | 2.33E-03 |
| $SO_2$ | - | - | 4.04E-03 | 1.45E-03 | 2.12E-03 |

### 5.2.4 Renewable Energy Curtailment and Resource Seasonality

One unexpected result was that despite the same or increased hydropower capacity in the 2040 and 2050 models, the magnitude of energy from hydropower was less than the 2019 model. In the 2040 model, there was a significant curtailment of hydropower[43], solar, and wind amounting to ~39% of the total annual load[44]. This curtailed energy could either be exported to neighboring

[42] The only value in this table that is in carbon-dioxide equivalent units.
[43] For hydropower, curtailment was the difference between the total annual energy constraint and total generation.
[44] See Appendix VIII for more plots of curtailment for the three models.

regions or stored through a large seasonal storage mechanism for use in the summer or low carbon-free system operation – like the summer (**Figure 5-7**). The seasonal variation of wind and solar resources can be seen clearly in **Figure 5-8**, which shows growing solar resource in the summer months coincident with a decline in the availability of wind. This seasonal event is challenging to manage because it occurs simultaneously with peak electrical demand in the summer – which is met by natural gas generation. Looking back to the annual curtailment in **Figure 5-7**, it can be seen that there is comparatively little curtailment occurring in the summer.

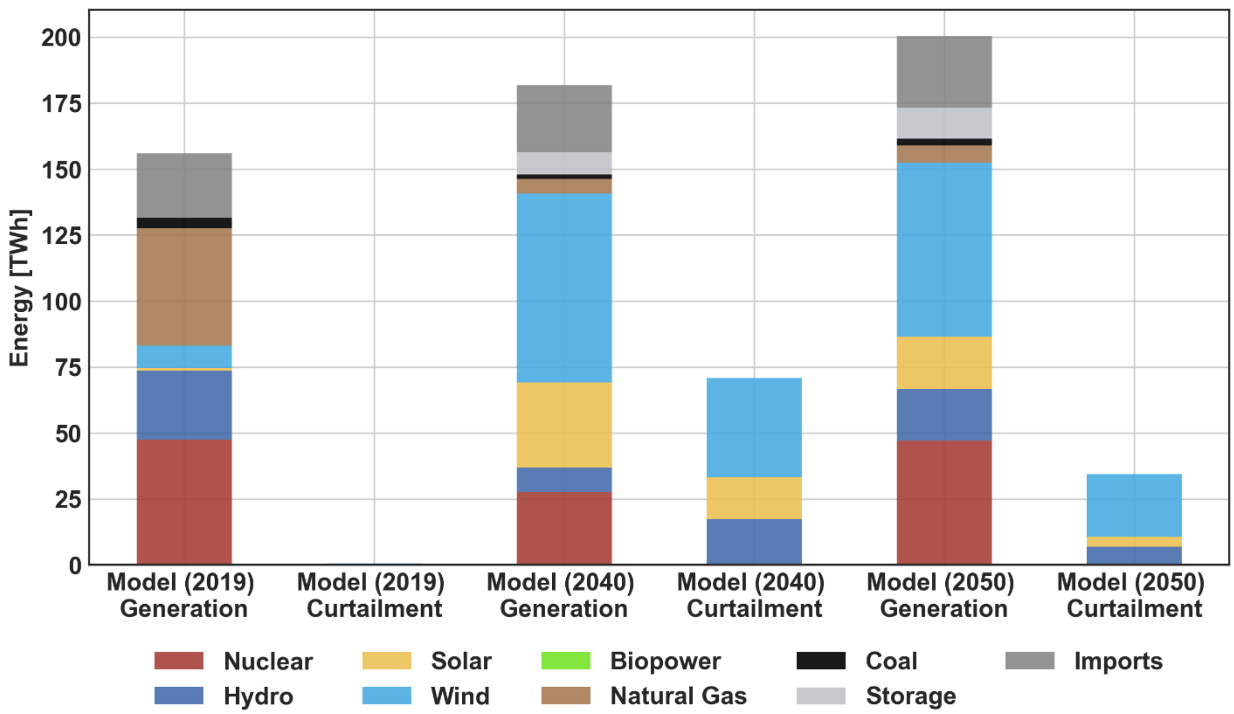


***Figure 5-6: Modeled Curtailment in the Context of Energy Generation.*** *Note: The models stochastically allocate curtailment between the renewable generators since they all have no marginal cost.*

***Table 5-4: Modeled Annual Curtailment.***

| Technology | Model (2019) | Model (2019) [% Of Total] | Model (2040) | Model (2040) [% Of Total] | Model (2050) | Model (2050) [% Of Total] |
|---|---|---|---|---|---|---|
| *Hydro* | 0.28 | 44 | 17.27 | 24 | 6.86 | 20 |
| *Solar* | 0.01 | 2 | 16.00 | 23 | 3.82 | 11 |
| *Wind* | 0.35 | 54 | 37.61 | 53 | 23.77 | 69 |
| ***Total Curtailment*** | 6.44 | 100 | 70.87 | 100 | 34.45 | 100 |

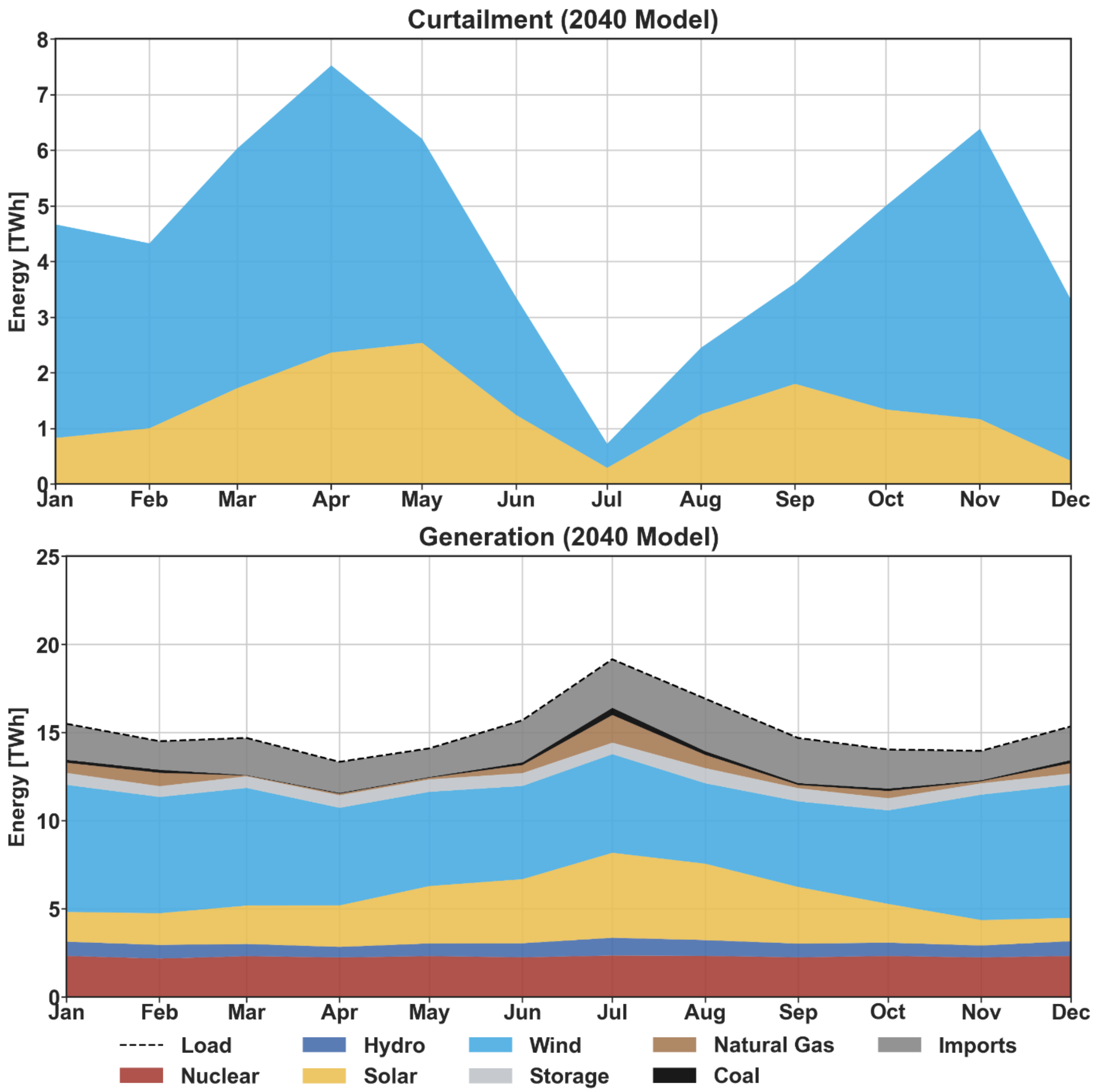


***Figure 5-7: Seasonality of 2040 Model Curtailment and Generation from Wind and Solar.*** *Note: The graph contains aggregate monthly values. There are significantly more solar resources in the summer than there is during the rest of the year.*

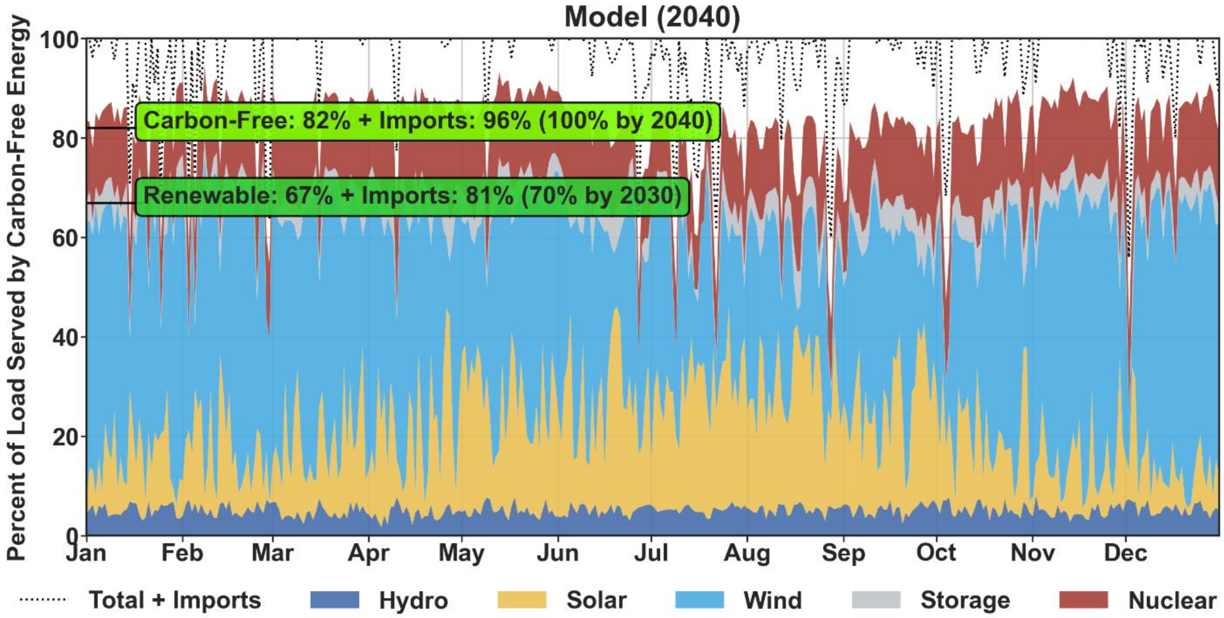


***Figure 5-8: 2040 Modeled Seasonal Variation in Monthly Energy Generation and Carbon-Free Operation.*** *Note: Appendix IX contains the same plots for the 2050 model. The dotted line in the carbon-free graphic shows the level of carbon-free energy which served load if all the imported energy procured by utilities from out of state came from carbon-free sources. Figure inspired by NYISO Power Trends 2020 [28].*

The fixed imports-exports profile was suspected to be a source of model inflexibility possibly driving excess curtailment in the model. The hypothesis was that the model might have been accepting out of state energy instead of using the energy available from renewables that would have otherwise been curtailed. If this were indeed happening, there would be a frequent occurrence of high curtailment during peak import periods. However, as seen in **Figure 5-9**, it does not seem like the fixed import profile was driving the curtailment in the 2040 model significantly.

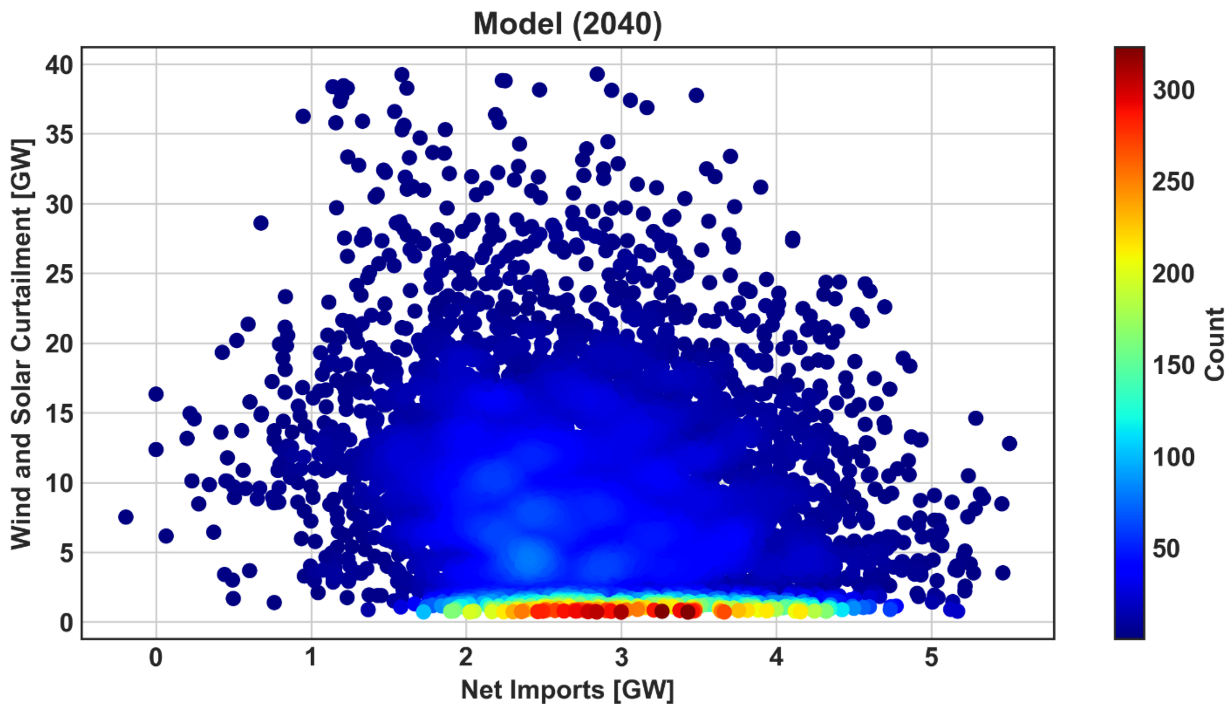


*Figure 5-9: Wind and Solar Curtailment's Relationship with Imports.*

### 5.2.5 Management of Resource Intermittency

Power systems with significant amounts of variable resources like wind and solar (2040 and 2050 Models), will need to be managed differently than systems with primarily thermal and hydropower generators (2019 Model). Mainly, the power systems will need to be able to react to changes in output from wind and solar quickly and reliably – this concept is called system *flexibility*. Flexibility has traditionally been provided by fast-acting fuel-based generators, like gas-powered combustion turbines, that can turn on and off quickly to meet changing demand or fill in during a sudden drop in supply from wind and solar. However, this traditional approach is not compatible with the renewable and carbon-free goals of the CLCPA in New York. As shown in **Figure 5-10**, peak solar production occurs around noon and falls off toward the evening as wind heads toward its peak in the early evening. **Figure 5-11** shows how the demand curve appears to the rest of the system after the supply from wind and solar is subtracted out – this is called the 'net-load'. This remaining load needs to be met reliably by the remaining power system. The net-load ramp is notably absent from the models, and that is due to a combination of storage and curtailment of the resource. The dotted line 2040 model in **Figure 5-11** gives the best picture of the possible net- load ramp that could have been created had battery storage not existed and curtailment not taken effect.

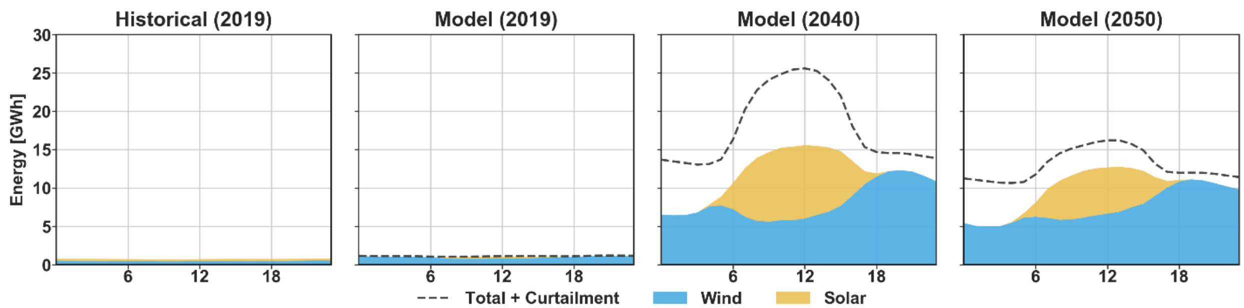


*Figure 5-10: Average Daily Generation from Renewable Sources (Models).*

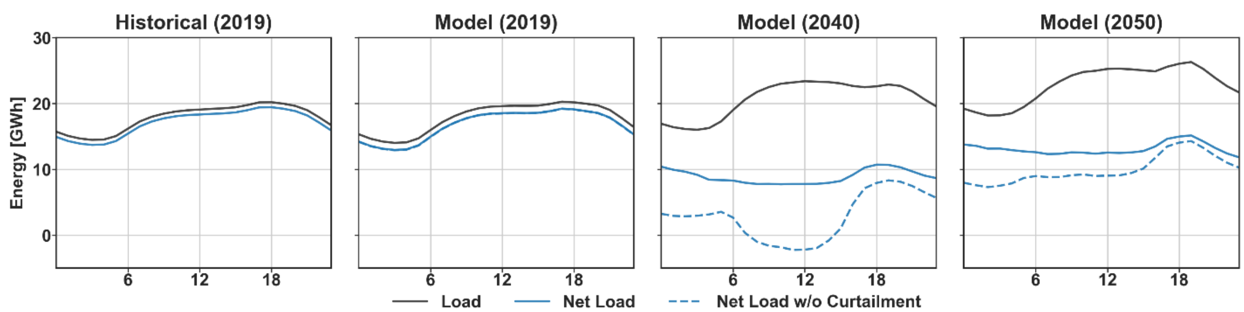


***Figure 5-11: Average Daily Load and Net Load (Modeled).*** *Note: The net load without curtailment line shows what the net load would have looked like had wind and solar energy not been curtailed. The net load w/o curtailment line does not include the additional seasonal load from storing the energy.*

**Figure 5-12** shows the average daily operation of the battery storage units in the three models. As a reminder, there is very little battery storage installed (33 [MW]) in 2019 and the assumption is that there is only four-hour storage capacity. In contrast, the 2040 and 2050 modes have significant amounts of eight-hour storage. **Figure 5-12** shows that batteries will charge when there is an abundance of solar in the middle of the day – thereby also reducing the amount of curtailment (**Figure 5-11**). Similarly, batteries charge in the evening when electricity prices are low and there are strong wind resources and low load. They also prepare to dispatch with the rising morning demand when wind production is decreasing and solar has not reached its peak. It should be noted that the battery modeling ensures that the battery returns to its initial charge state (assumed to be 50%) by the end of the day so it can start the following day in the same condition – which explains why there is not a smooth transition between the charge and discharge states between the start and end of the day. Appendix XI Seasonal Operation of Battery Storageshows the seasonal variation of battery storage.

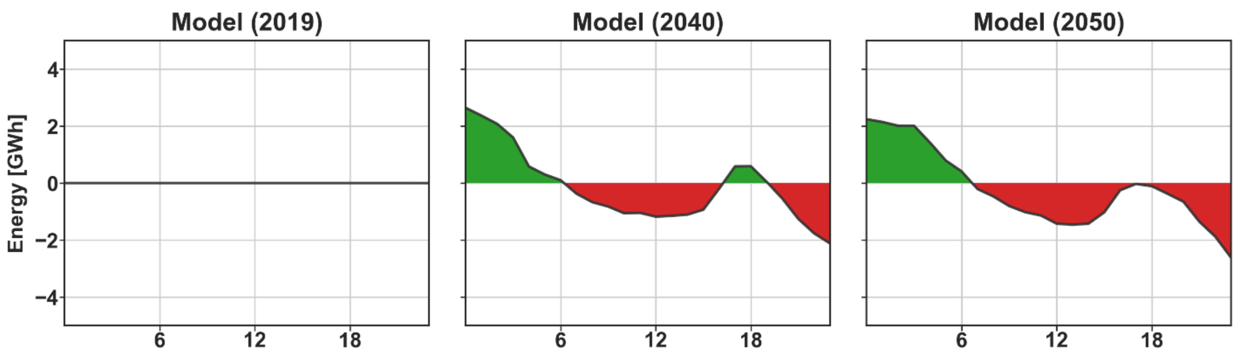


*Figure 5-12: Modeled Average Daily Battery Storage Operation. Note: The periods in red indicate when the battery is acting as a load to the grid due to charging, and the green indicates when the battery is dispatching to provide energy to help meet the load.*

## 5.2.6 Intrastate Flow

The flow of energy between the upstate and downstate region (4.3 Topology) can provide some insight into future instate-transmission needs. **Table 2-1** summarizes the transmission constraints that were used in the three constructed models.

*Table 5-5: Modeled Transmission Constraints.*

| | Model (2019) | Model (2040) | Model (2050) |
|---|---|---|---|
| *Max Flow (GW)* | 4.05 | 20 | 30 |

As seen in **Figure 5-13**, the models show that the on an average the amount of flow from the upstate to the downstate region capacity at a minimum would need to roughly triple; this would be needed to meet the demand in the downstate region that is especially high in the evening hours.

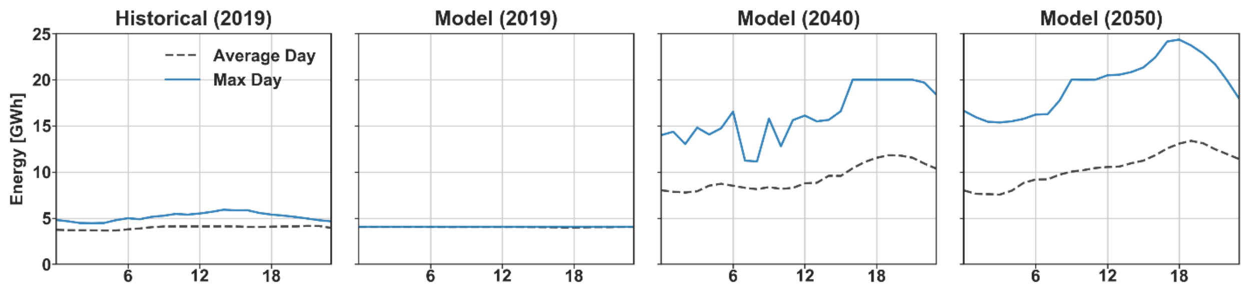


*Figure 5-13: Average and Max Daily Intrastate Flow. Note: Positive values indicate flow from the upstate region to the downstate region. The Historical (2019) probably exceeded the normal 4.05 [GW] limit to ensure the load was met.*

Although the average transmission capacity might need to at least triple, the transmission capacities would need to be able to deliver power on the days with the highest need for transmission capacity. **Figure 5-13** also shows individual days that contained a maximum transmission flow. During these days, the transmission system in the 2019 and 2040 models hit their respective maximums – but it did not in the 2050 model. More detailed power flow studies could be conducted to analyze what would be the necessary sized transmission capacity. However, it seems that the 2040 and 2050 model would need about 20 [GW] and 25 [GW] respectively to reliably deliver power on these days.

### 5.2.7 Generation Cost Comparison

Aggregating the generation costs from a production cost simulation can allow for estimating the operational cost of a grid system. Although it does not include all costs, like fixed costs or capital costs, it is still a useful metric to compare how much money will need to be spent every year to produce electricity. **Figure 5-14** shows a generation cost comparison between the models, which indicates that the total and average costs could decline to about 20% relative to the 2019 model costs. Information about the historic 2019 cost of generation was not available.

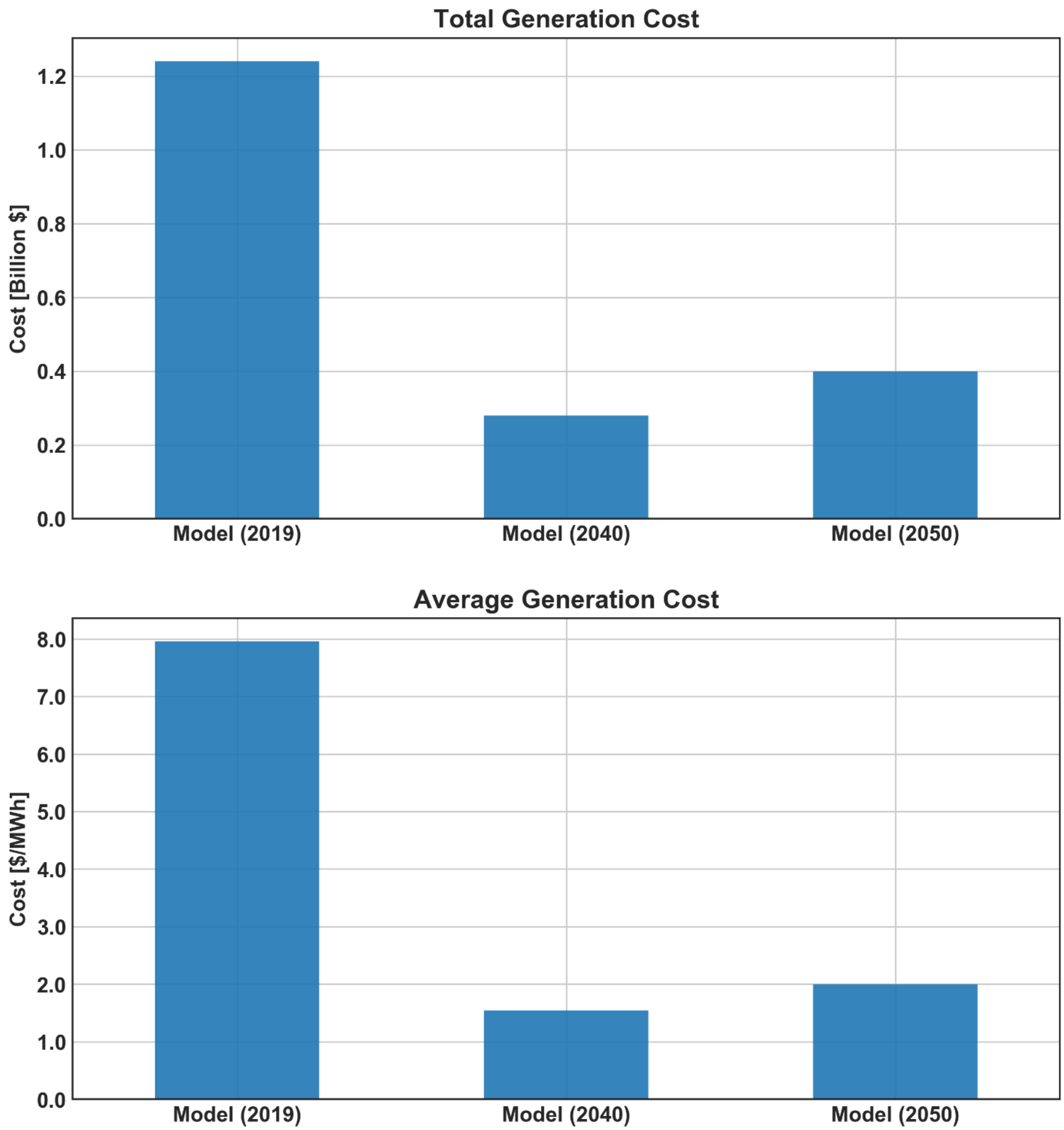


***Figure 5-14: Annual and Average Production Cost.*** *Note: Units in 2017 dollars. According to Plexos documentation the total production/generation cost includes fuel, VO&M, start and shutdown costs, and emissions costs. However, only fuel and VO&M costs were included in the constructed models.*

## 5.3 Reliability Assessment

Production cost models can be useful for identifying events that may be a concern for system reliability; these events can be analyzed on a high level and then further analyzed in power flow studies if necessary. Interesting events to analyze include peak load, peak variable renewable energy production (wind and solar), and significant wind ramping events - **Figure 5-15**, **Figure 5-16**, **Figure 5-17** show snapshots of such events for each model.

Peak load for the three models occurs on July 19$^{th}$ at slightly different times due to the impact of storage charging on load (**Figure 5-15**). As expected, the peak load in the future models is higher in the 2040 and 2050 models (40 [GWh]) compared to the 2019 model (32 [GWh]). In the 2019 model, a significant amount of natural gas and coal generation dispatches to meet peak load – the same is true for the surrounding days. However, in the future models there is a significant difference; on the day of peak load, there is coincidentally peak wind and solar resource (**Figure 5-16**), which (with the help of storage) prevents the need to dispatch fossil fuel generation completely in the 2040 model. This demonstrates that with enough wind and solar resource, the system can meet the peak loads of the state; when not enough resource is available then fossil-fuel-based generators need to be dispatched– evidenced by the operation in adjacent days of the 2040 model (**Figure 5-15**).

Since wind and solar resources are variable, its also useful to study how system operation changes when they vary in output significantly. Although wind and solar are often complimentary, this ramping analysis focuses on wind since it is the primary energy source in the future; similar ramping analyses could be conducted for solar and the two variable resources in tandem. **Figure 5-17** shows the biggest wind ramps (both positive and negative) that occurred in the three models (ramps of 1-24 hours in duration were considered). The largest ramp in the 2019 model barely changes normal operation due to low installed wind capacity, but in the future models the ramps were significantly more impactful. In the 2040 model, the largest ramp occurred over 13 hours during which the wind resource increased by 21 [GWh]. During this significant increase in wind generation, the system operated completely carbon-free (not including imports) after a strong day of solar energy production. Excess wind resource is likely used to charge batteries during this period which helps meet demand in the early morning of the following day.

In the 2050 model, the largest wind ramping event is a 22 [GWh] down-ramp that occurs at 11 PM on November 10$^{th}$ over 7 hours. During this event, wind production drops to near zero during the early morning of November 11$^{th}$. However, battery storage capacity plays a critical role in filling this gap for several hours before the wind picks back up. This event highlights one of the important roles that short-duration storage will play in a future power system with significant amounts of variable resources like wind and solar. Without the temporal flexibility that short duration storage provides, fossil fuel-based resources will need to be dispatched to meet the load – pushing NY further away from meeting the decarbonization goals of the CLCPA.

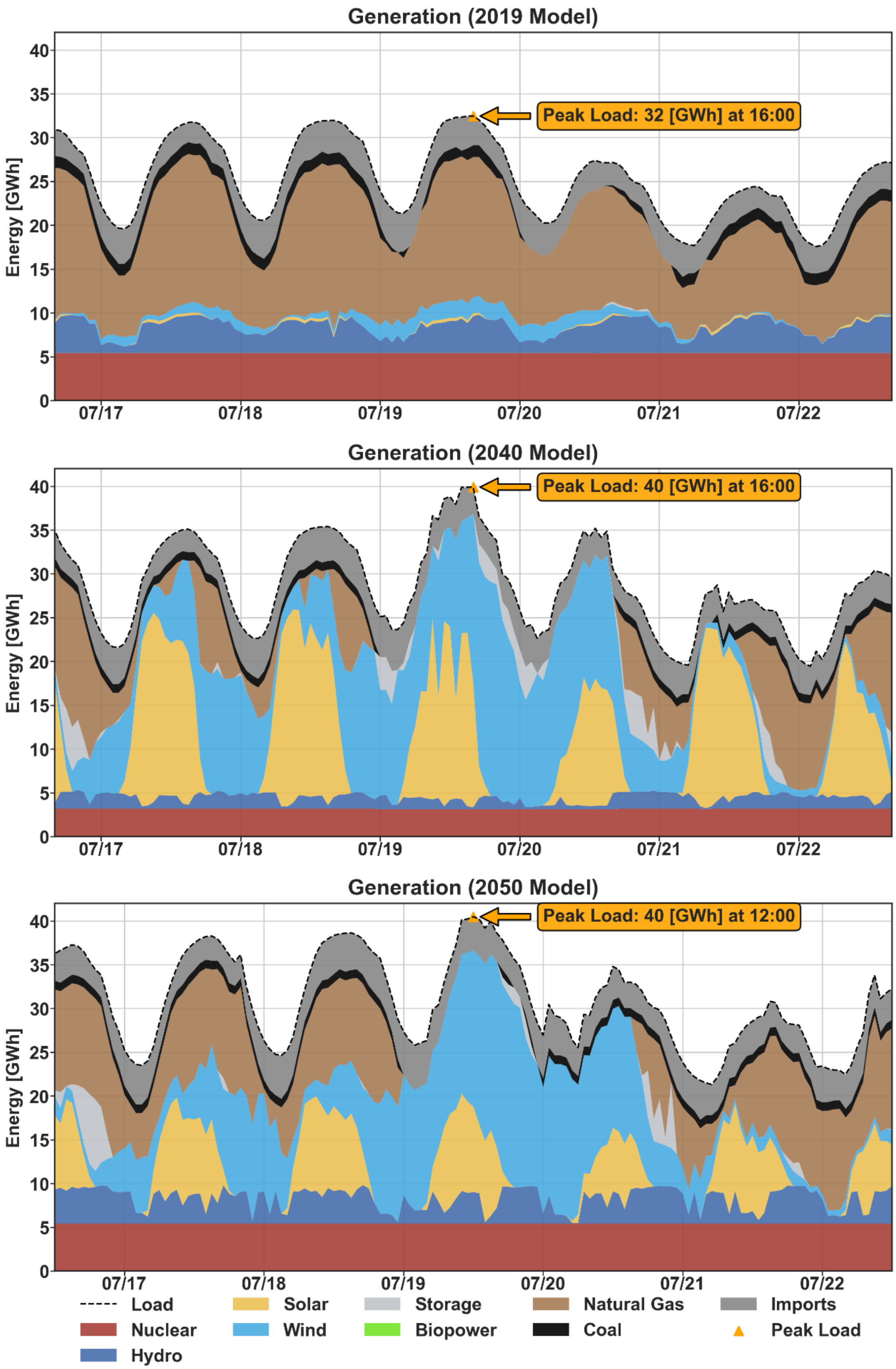


*Figure 5-15: Model Operation During Peak Load*

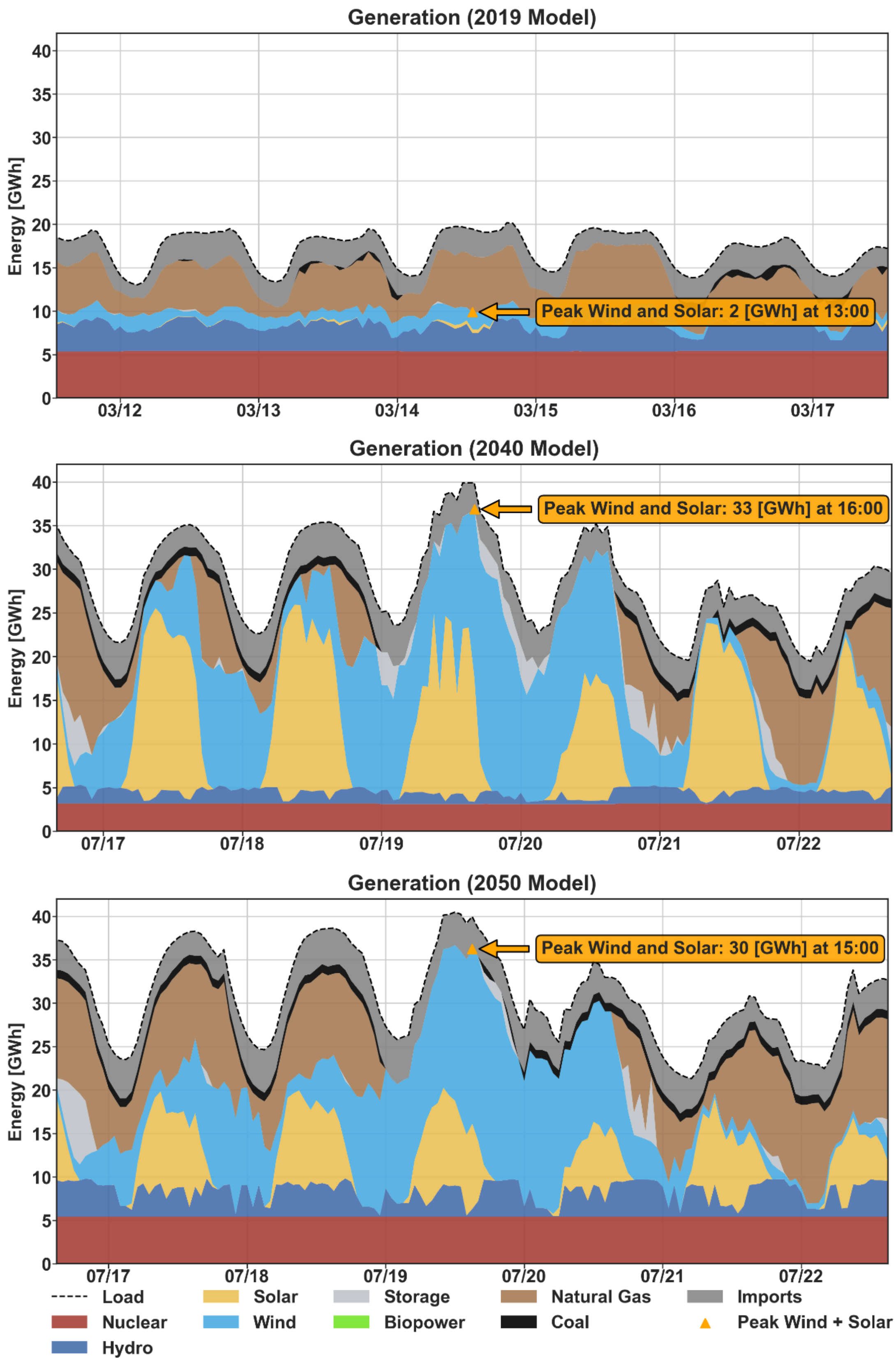


*Figure 5-16: Model Operation During Peak Wind and Solar Generation*

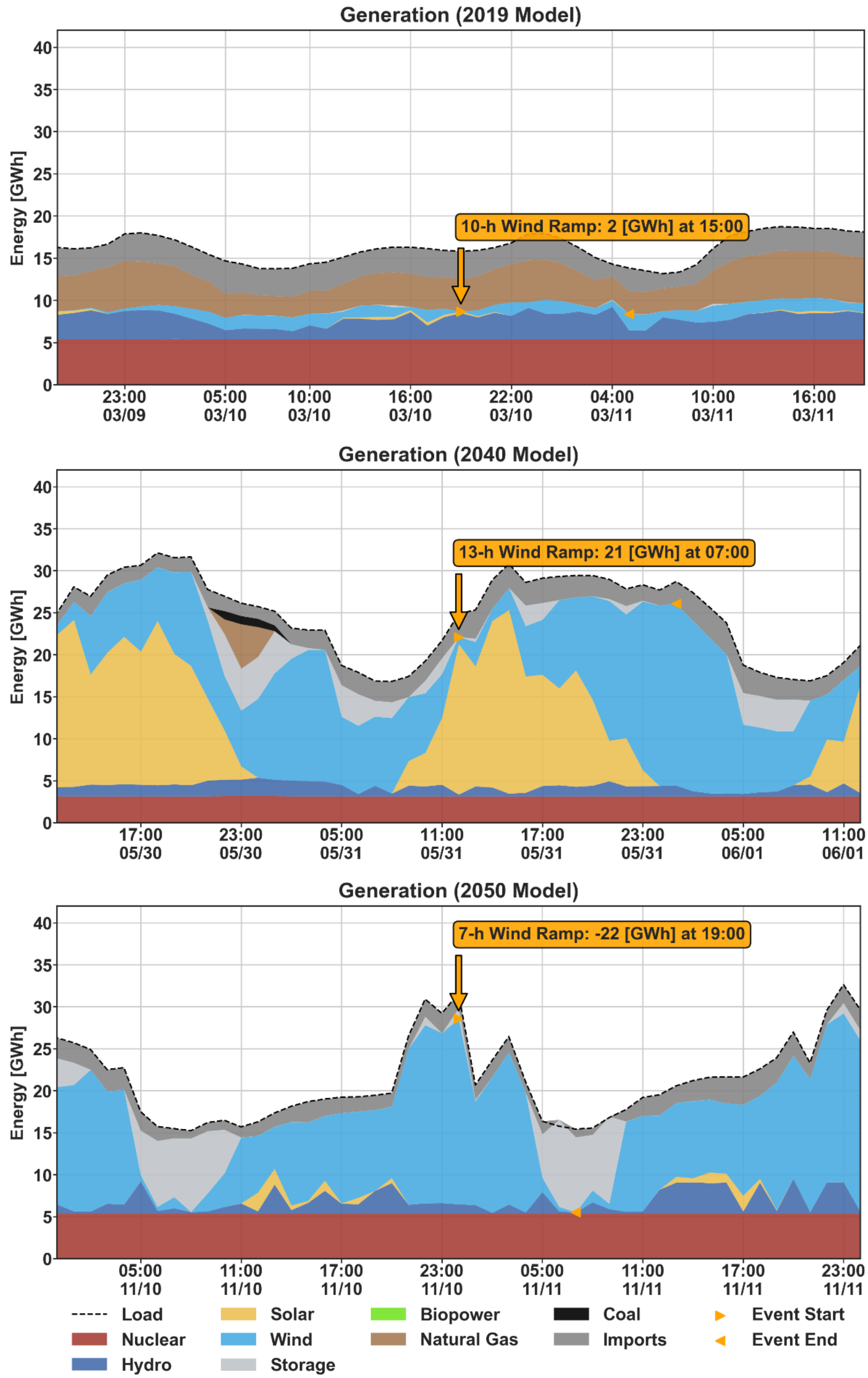


*Figure 5-17: **Model Operation During Peak Wind Ramping Events.** Note: Ramping events spanning 1-24 hours in duration were considered. See Appendix XII for a list of top events for each model.*

## 5.4 Future Work

The study could be improved by implementing a curve-based methodology for modeling the deployment of new solar and hydropower resources. The availability of the Wind Toolkit dataset for wind made it significantly easier to accurately model its deployment. In the absence of such a dataset for solar, more analysis on selecting sites that are representative of the resource of the upstate and downstate region could be done. Furthermore, hourly supply profiles for hydropower would improve the accuracy of the operation of these plants. As a result of the energy-based methodology used, the hydropower facilities would essentially turn off in the evenings – which is not that accurate. Furthermore, modeling of maintenance events for generators would help analyze system reliability.

Even though the two-node model was fairly accurate, a topology with more nodes – such as one for each NYISO region would more accurately capture the dynamics of the power system and provide more granular results. For example, specific NYISO transmission lines that need their capacity increased could be identified. This information could be acquired, but it would be necessary to file a Critical Infrastructure Information request with the State.

The import and export model could be improved by using a market-based methodology rather than assuming the net import to load ratio remains the same. This would allow for modeling to capture when it would make economic sense to export renewable energy resources. The demand model could be improved by taking into account the impact of demand response programs, as well as how the shape of electric demand might change as a result of electrification economywide – including the electrification of transportation over the next few decades.

Lastly, a capacity expansion model could be constructed from scratch instead of using the capacity expansion results from literature studies. This was attempted for this study but stifled by some infeasibility issues and impending deadlines. This would enable a scenario-based analysis with sensitivities studies varying cost and policy assumptions. In other words, it would help answer the question 'what should the system look like to achieve the goals of the CLCPA' rather than analyzing 'does this system achieve the policy goals'.

## 5.5 Conclusion

New York's ambitious clean energy goals specified by the CLCPA are feasible but would be difficult to achieve. The models indicate the power system could evolve from approximately 52% carbon-free to 82% without imports (or 96% including imports). The carbon-free capacity would be driven by wind and solar, that increase renewable energy source from serving 23% of the load to more than 58%. Notably, both future scenarios fall short of the 100% carbon-free goal by 2040. Nonetheless, the specified configurations could enable a power system with about 20% of the current instate-emissions. Decarbonizing New York's power sector, the state's third-largest polluting industry, would play a critical role in achieving a lower polluting economy overall.

The models show that there is a need for seasonal storage to achieve the goals of the CLCPA. The curtailment of renewable sources in the 2040 model amounted to about 39% of the total statewide load, which could have been used to achieve the goals and become an exporter of clean energy to surrounding regions. Seasonal storage is needed to manage the seasonal supply and demand mismatch between variable renewable resources and load. Variable wind and solar resources need to be managed with carbon-free flexible solutions like batteries and demand response. Eight-hour batteries could provide flexibility by reducing renewable energy curtailment when there is excess supply. This study also supports the claim that a future power system with significant wind and solar can be reliably operated during peak load periods and significant wind ramping events. Short duration storage plays a crucial role in providing flexibility for these systems during, before, and after these events. Notably, nuclear may have an important role to play in providing consistent baseload carbon-free power to augment variable wind and solar resources. Furthermore, 2 to 5 times the current transmission capacity would need to aid the delivery of renewable resources from the upstate region to downstate. At 20% of the current annual generation costs, the future power system could also become significantly cheaper to operate.

This case study for New York's climate goals provides a glimpse into how challenging decarbonizing infrastructure could be. These types of analyses are critical to coordinating the clean energy transition and informing stakeholders about the range of possible solutions. I am hopeful that New York and the rest of the world will rise to this formidable challenge.

# Appendix I NYISOToolkit

In the process of completing my thesis research, I developed a toolkit for downloading, analyzing, and creating visualizations of NYISO data. The toolkit was featured in Issue 460 of the Python Weekly Newsletter. The toolkit solves several problems, including issues related to data quality – like missing time zone information and missing data at the expected frequency. I released this as an open-source python library on GitHub to help others get over the numerous roadblocks that it takes to get the NYISO data in a usable form for analysis. Furthermore, I made it to help track the progress toward the CLCPA goals. Some of the visualizations supported by the library can be found throughout the report such as the historic 2019 components of **Figure 5-1** and **Figure 5-2**.

Access the open-source library at https://github.com/m4rz910/NYISOToolkit

## Appendix II A Few Simple Production Cost Scenarios

All of the following examples are based on Plexos' Power System Modeling 101 documentation [39].

**Case 1**

Consider a simple grid (**Figure II-1**) consisting of two generators that need to serve a load (demand) (L) of 150 [MW] for one hour. Before dispatching (or turning on) the generators, it is necessary to determine which one(s) to dispatch (Security Constrained Unit Commitment) and at what power level to successfully meet the demand at the lowest operational cost (Security Constrained Economic Dispatch). Independent system operators perform this optimization to ensure reliable and affordable system operation over various time scales, from few minutes to multiple days ahead of time.

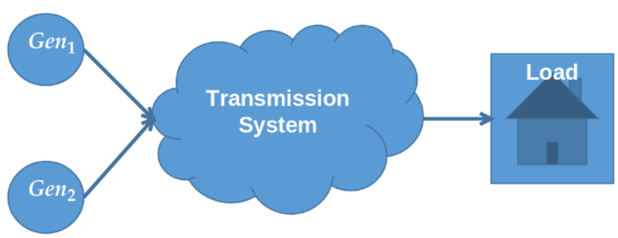


*Figure II-1: Simple Grid*

If the marginal cost of production for two generators are known to be $c = \begin{bmatrix} 15 \\ 25 \end{bmatrix}$ and the maximum capacities of the generators ($x_i^{max} = \begin{bmatrix} 200 \\ 150 \end{bmatrix}$), logic dictates that Generator 1($\mathrm{G}_1$) can operate at a lower cost than Generator 2 ($\mathrm{G}_2$), and is capable of completely meeting the total load independently. $\mathrm{G}_2$ will not get dispatched. $\mathrm{G}_1$ is selected (or *committed*) over $\mathrm{G}_2$ because generators are selected to meet load in merit order (market rule 1). This scenario can be expressed as a linear program:

$$C_{prod} = \sum_{i=1}^{N} c_i * x_i \text{, } \min(C_{prod}) \;\; s.t\ constraints: \begin{matrix} x_1 + x_2 = 150 \\ 0 \le x_1 \le 200 \\ 0 \le x_2 \le 150 \end{matrix}$$

The solver finds for the column vector x, which contains the power dispatch [MW] from each generator. In this case, $x = \begin{bmatrix} 150 \\ 0 \end{bmatrix}$, which means $G_1$ will have an output $x_1 = 150\ MW$ and $G_2$ will have none — just as initially predicted. The total production cost of the system can be calculated:

$$C_{prod} = c^T x = 150\ [MW] * 15\ [\$/MWh] + 0\ [MW] * 25\ [\$/MWh] = 2250\ [\$/hr] = C_1$$

This represents the lowest total system production cost while meeting all the constraints. To calculate the cost to load ($C_{load}$) the market price ($P_m$) is needed. The most basic market rule is that $P_m$ is set by the marginal generator's production cost. A marginal generator is a generator that provides the last unit of power necessary to meet demand — in this case Generator 1 is the only generator on, so it sets the market price at its production cost, of $c_1 = 15\ [\$/MWh]$. Using Equations 3 and 4 the cost to load and total system profit are can be calculated:

$$C_{load} = P_m * L = 15\ [\$/MWh] * 150\ [MW] = 2250\ [\$/h]$$

$$P_{total} = C_{load} - C_{prod} = 2250\ [\$/h] - 2250\ [\$/h] = 0\ [\$/h]$$

In this special case, there no total profits and $G_1$ receives $2250\ [\$/h]$ in revenue which will cause it to break even (Equations 5 & 6).

$$R_1 = x_1 * P_m = 15\ [\$/MWh] * 150\ [MW] = 2250\ [\$/h]$$

$$P_1 = R_1 - C_1 = 2250\ [\$/h] - 2250\ [\$/h] = 0\ [\$/h]$$

The fact the $G_1$ does not make any profit may seem strange, but this happens to the marginal generator in every scenario. This is demonstrated more clearly when more than one generator gets dispatched — like in Case 2.

**Case 2**

In Case 2, consider the same problem as Case 1 but the load is increased to 250 MW, which is greater than the maximum capacity of $G_1$; using the outcome from Case 1, it is expected that both generators will be dispatched this time. Now the linear program will have an updated new equality constraint $x_1 + x_2 = 250$. The optimal dispatch is $x = \begin{bmatrix} 200 \\ 50 \end{bmatrix}$, which means $G_1$ is producing power at its maximum output and $G_2$ provides 50 [MW]. The total system cost of production is:

$$C_{prod} = c^T x = 200 * 15 + 50 * 25 = 4250 \, [\$/hr]$$

In this case, the $G_2$ is the marginal generator since generators are selected to meet load in merit order — meaning those with lower production cost are selected to contribute their capacity before more expensive ones. $G_2$ provided the last unit of power necessary to fully meet the demand of 250 [MW]. As mentioned in Case 1, the marginal generator always sets the market price, which is now 25 [$/MWh].

$$C_{load} = P_m * L = 25 \, [\$/MWh] * 250 \, [MW] = 6250 \, [\$/h]$$

$$P_{total} = C_{load} - C_{prod} = 6250 \, [\$/h] - 4250 \, [\$/h] = 2000 \, [\$/h]$$

Total profits amount to 2000 [$/h] which in this case belong to $G_1$, and $G_2$ as the marginal generator breaks even because it is paid exactly its marginal cost.

$$R_1 = x_1 * P_m = 200 \, [MW] * 25 \, [\$/MWh] = 5000 \, [\$/h]$$

$$R_2 = x_2 * P_m = 50\ [MW]\ *\ 25\ [\$/MWh]\ \ =\ 1250\ [\$/h]$$

$$P_1 = R_1 - C_1 =\ 5000\ [\$/h]\ -\ (200\ [MW]\ *\ 15\ [\$/MWh])\ =\ 2000\ [\$/h]$$

$$P_2 = R_2 - C_2 =\ 1250\ \left[\frac{\$}{h}\right] - \left(50\ [MW] *\ 25\ \left[\frac{\$}{MWh}\right]\right) =\ 0\ \left[\frac{\$}{h}\right]$$

**Case 3**

What happens when a generator is constrained by a transmission line instead of its maximum capacity? This case is important to consider because it is not immediately clear which generator is marginal and what the compensation for each generator should be. Case 3 is the same as Case 3, except that the transmission line connected to Generator 1 will overload if it surpasses 180 MW. Factoring in the new constraint, the new formulation is:

$$Constraints: \begin{array}{c} x_1 + x_2\ =\ 150 \\ 0 \le x_1 \le 200 \\ 0\ \le x_2 \le 150 \\ \boldsymbol{x_1 \le 180} \end{array}$$

Solving the linear program, the dispatch which minimizes system production cost while maintaining all constraints is now $x\ = \begin{bmatrix} 180 \\ 70 \end{bmatrix}$ resulting in:

$$C_{prod} = c^T x\ =\ 180\ [MW] * 15\ [\$/MWh] +\ 70\ [MW] * 25\ [\$/MWh] =\ 4450\ [\$/hr]$$

Both generators are operating below their maximum capacity, so what is the marginal generator, and what is the market price? When a generator is constrained off by transmission, it is not the marginal generator and therefore does not set the market price — it receives revenue equal to its marginal cost of generation. For a generator to receive the market price they must be producing power at their maximum capacity. $G_2$ is the marginal generator and it sets the market price to 25 [$/MWh] and breaks even, and $G_1$ makes a lower profit (1800 [$/h]) than it did in Case 2.

$$C_{load} = P_m * L = 25 [\$/MWh] * 250 [MW] = 6250 [\$/h]$$

$$P_{total} = C_{load} - C_{prod} = 6250 [\$/h] - 4450 [\$/h] = 1800 [\$/h]$$

$$R_1 = x_1 * P_m = 180 [MW] * 25 [\$/MWh] = 4500 [\$/h]$$

$$R_2 = x_2 * P_m = 70 [MW] * 25 [\$/MWh] = 1750 [\$/h]$$

$$P_1 = R_1 - C_1 = 4500 [\$/h] - (180 [MW] * 15 [\$/MWh]) = 1800 [\$/h]$$

$$P_2 = R_2 - C_2 = 1750 [\$/h] - (70 [MW] * 25 [\$/MWh]) = 0 [\$/h]$$

**Case 4**

The power system problems in Cases 1-3 had linear and continuous generator decision variables (between zero (off) and their maximum output). However, many generators have a minimum power output (for stability reasons) which requires adding a binary decision value to the generator constraints. The generator can be off, or it can be on and delivering power between the minimum and maximum output levels; the discontinuous nature of this domain of output means that necessitates the introduction of a binary decision variable to encode the on (1) or off (0) state of the generator. The optimization problem can now be classified as a mixed-integer program because there are now linear and binary decision variables. The objective function remains unchanged – it is still linear.

$$New\ Constraints: \begin{matrix} x_1 + x_2 = 150 \\ x_1^{min} * u_1 \le x_1 \le x_1^{max} * u_1 \\ x_2^{min} * u_2 \le x_2 \le x_2^{max} * u_2 \end{matrix}$$

$$where\ ...$$

$$x_i^{min}\ and x_i^{max} - generator\ i's\ minimum\ and\ maximum\ power\ output$$

$$u_i - generator\ i's\ binary\ on\ (1)\ or\ off(0)\ status$$

Using the same demand and $P_{g,i}^{max}$constraints from before, if the minimum power outputs are: $P_{g,1}^{min} = 100\ [MW]$ and $P_{g,2}^{min} = 100\ [MW]$ the optimal dispatch changes to $x\ = \begin{bmatrix} 150 \\ 100 \end{bmatrix}$. Although the $G_1$ is cheaper and available to provide up to 200 [MW] will not be dispatched because the remaining load would be 50 [MW] and $G_2$ can only provide a minimum of 100 [MW]. Cost and profit can be calculated in the same fashion as in other cases.

A brief theoretical discussion on the number of solutions to the optimization problem: The constraints can be expressed as the matrix equation $Ax\ \leq\ b$. A would not be square, which means that if the constraint was $Ax\ =\ b$ , there would either be no solution or only one solution [40]. However, the constraint is an inequality, which means that there are most likely (because a fundamental responsibility of power system planners is to ensure there is enough capacity to meet demand) multiple solutions that will satisfy the constraint. The objective function is then used to search for which solution vector will minimize the overall system cost.

# Appendix III NREL Standard Scenario Results for NY

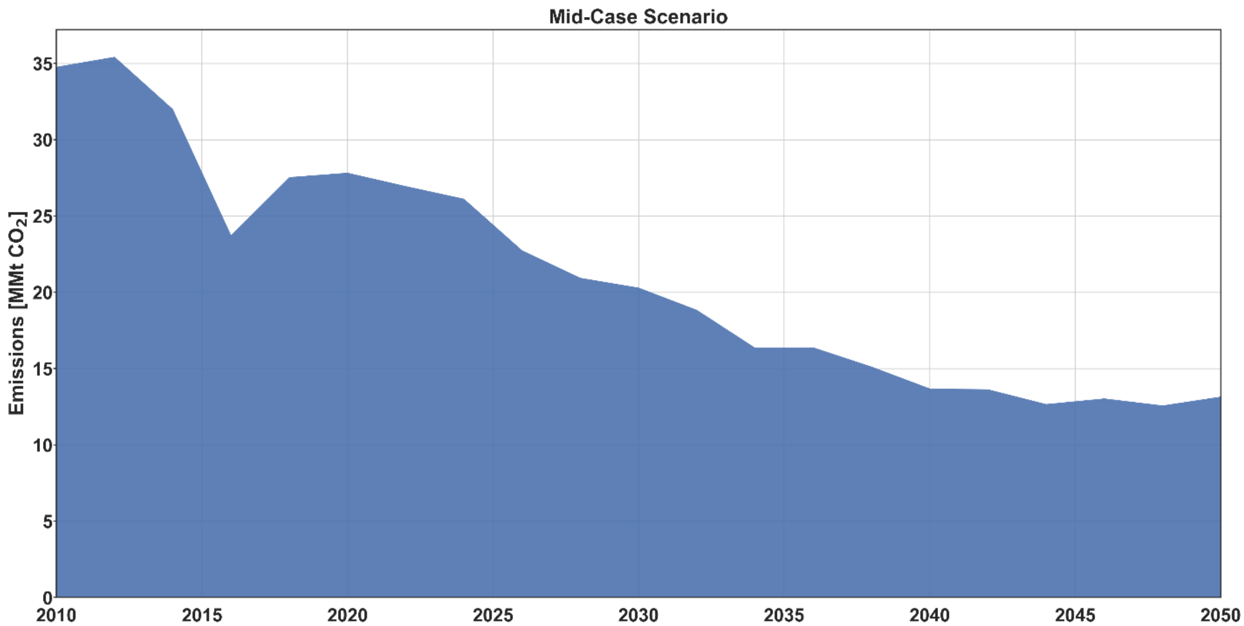


***Figure III-1: Emissions Over Time in New York.*** *Source: NREL Standard Scenarios Study (Mid-Case Scenario) [2]*

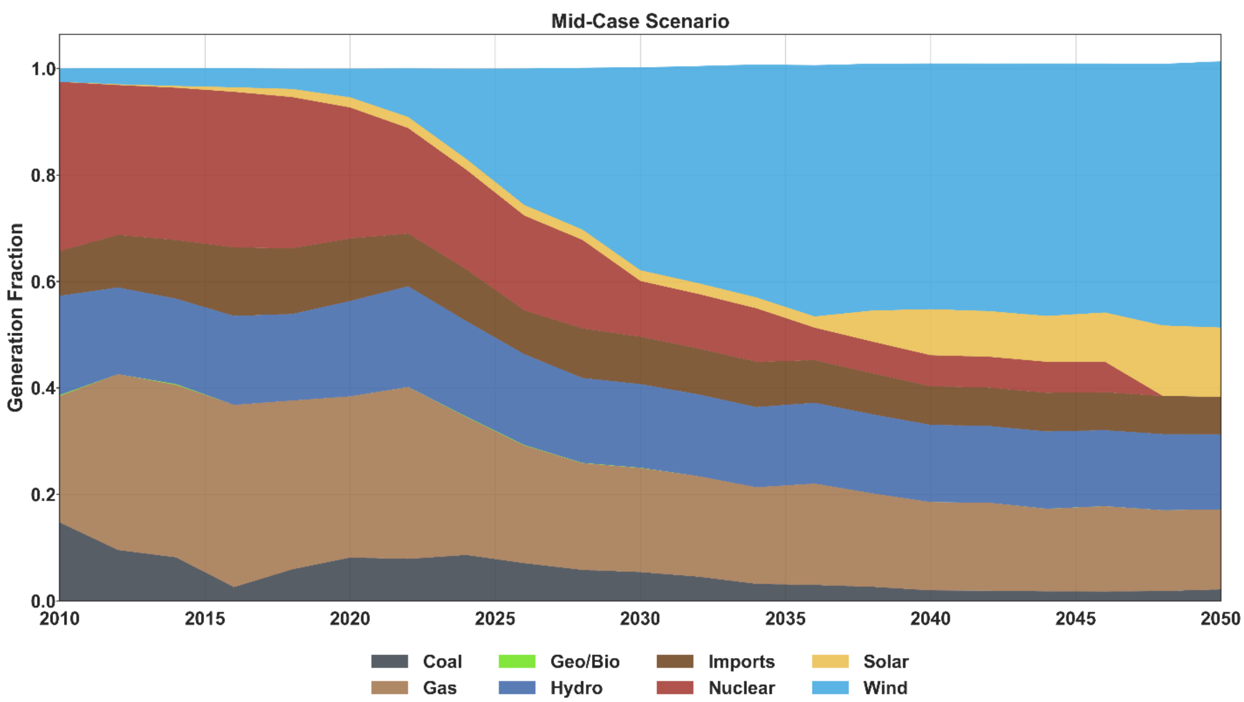


***Figure III-2: Generation Fraction Over Time in New York.*** *Source: NREL Standard Scenarios Study (Mid-Case Scenario) [2]*

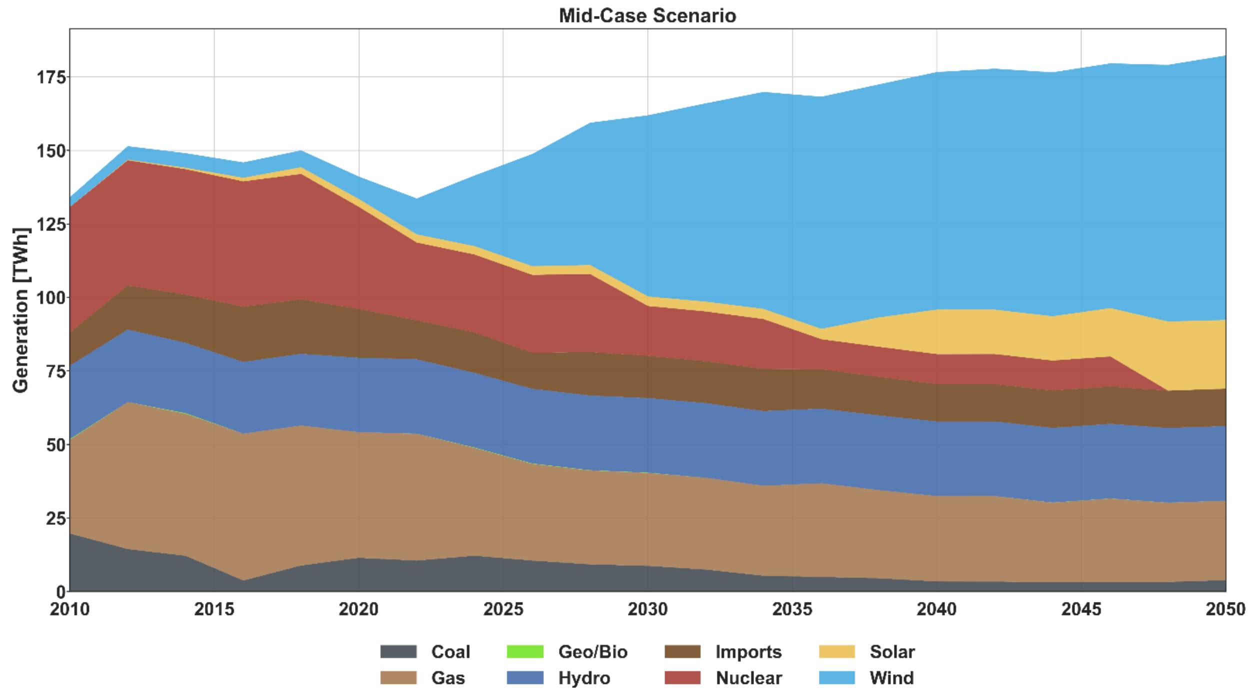


***Figure III-3: Generation Over Time in New York.*** *Source: NREL Standard Scenarios Study.*

***Table III-1:Capacity [GW] Over Time in New York.*** *Source: NREL Standard Scenarios Study [2]*

| Year | Coal | Gas | Geo/Bio | Hydro | Imports | Nuclear | Solar | Storage | Wind |
|---|---|---|---|---|---|---|---|---|---|
| *2010* | 2.68 | 24.51 | 0.13 | 4.44 | 1.47 | 5.39 | 0.01 | 1.41 | 1.27 |
| *2012* | 2.67 | 24.77 | 0.13 | 4.44 | 1.95 | 5.39 | 0.16 | 1.43 | 1.63 |
| *2014* | 2.22 | 24.62 | 0.13 | 4.44 | 2.14 | 5.39 | 0.36 | 1.43 | 1.74 |
| *2016* | 1.69 | 24.59 | 0.07 | 4.44 | 2.45 | 5.39 | 0.89 | 1.43 | 1.82 |
| *2018* | 1.69 | 25.09 | 0.07 | 4.44 | 2.42 | 5.39 | 1.61 | 1.43 | 1.98 |
| *2020* | 1.69 | 25.22 | 0.07 | 4.59 | 2.16 | 4.39 | 1.90 | 1.93 | 2.47 |
| *2022* | 1.69 | 23.88 | 0.09 | 4.59 | 1.72 | 3.35 | 1.97 | 2.43 | 3.58 |
| *2024* | 1.69 | 23.59 | 0.09 | 4.62 | 1.79 | 3.35 | 2.03 | 2.93 | 6.56 |
| *2026* | 1.69 | 23.18 | 0.09 | 4.62 | 1.60 | 3.35 | 2.11 | 3.43 | 10.11 |
| *2028* | 1.69 | 23.07 | 0.09 | 4.62 | 1.93 | 3.35 | 2.20 | 3.93 | 12.75 |
| *2030* | 1.54 | 22.68 | 0.09 | 4.62 | 1.87 | 2.14 | 2.33 | 4.43 | 16.20 |
| *2032* | 1.54 | 22.49 | 0.09 | 4.62 | 1.85 | 2.14 | 2.41 | 4.43 | 17.77 |
| *2034* | 1.21 | 21.53 | 0.09 | 4.62 | 1.87 | 2.14 | 2.49 | 4.43 | 19.47 |
| *2036* | 1.02 | 20.96 | 0.09 | 4.62 | 1.74 | 1.29 | 2.62 | 4.43 | 20.85 |
| *2038* | 1.02 | 19.64 | 0.09 | 4.62 | 1.71 | 1.29 | 6.12 | 4.43 | 20.66 |
| *2040* | 1.02 | 18.68 | 0.04 | 4.62 | 1.65 | 1.29 | 9.05 | 4.43 | 20.83 |
| *2042* | 1.02 | 19.13 | 0.02 | 4.62 | 1.65 | 1.29 | 9.12 | 4.43 | 21.00 |
| *2044* | 1.02 | 18.37 | 0.02 | 4.62 | 1.65 | 1.29 | 9.21 | 4.43 | 21.36 |
| *2046* | 1.02 | 19.23 | 0.02 | 4.62 | 1.65 | 1.29 | 10.40 | 4.43 | 21.40 |
| *2048* | 1.02 | 18.25 | 0.02 | 4.62 | 1.65 | 0.00 | 14.09 | 4.43 | 22.25 |
| *2050* | 1.02 | 15.50 | 0.02 | 4.62 | 1.65 | 0.00 | 14.09 | 11.62 | 22.63 |

## Appendix IV Load Scaling Script

```
import pandas as pd
import pathlib as pl


def scale_load_energy():
    ## 2019 Real Hourly Load [MW] - Infrastructure Year
    dataset = 'load_h'; infra_year = '2019'
    file = pl.Path(operation_nysio_dir,'{}_{}.pkl'.format(infra_year, dataset))
    load_2019 = pd.read_pickle(file).tz_convert('US/Eastern').rename(columns=nyiso_regions) #MW
    load_mwh_2019 = pd.DataFrame((load_2019 / 1000 * 1).sum(axis='index')).T #MW -> GWh
    load_mwh_2019.index = ['2019-01-01 00:00:00']

    ## Goldbook Energy Growth Forecast (2020-2050) [GWh]
    df=pd.read_csv(pl.Path(nysio_goldbook_dir,'regional_load_table.csv'), index_col=0)
    df.index = pd.to_datetime(df.index, format='%Y')
    df = pd.concat([load_mwh_2019, df]) # combine 2019 actual with 2020-2050 predictions
    df.index = pd.to_datetime(df.index)

    ## Plot Annual ENERGY Growth statewide
    df['NYCA'] = df.sum(axis='columns') - df['NYCA'] # overwrite statewide column with sum of smaller regions (they were 99.68% the same anyway)
    baseline_load_growth = df['NYCA']
    fig, ax = plt.subplots(figsize=(10,5),  dpi=300)
    (baseline_load_growth / 1000).plot(kind='line', ax=ax)  # convert GHW to TWH
    plt.ylim(0,195)
    plt.ylabel('Annual Energy (TWh)')
    #ticks
    plt.xticks(df.index,rotation=0)
    for tick in ax.xaxis.get_major_ticks() + ax.yaxis.get_major_ticks():
```

```
        tick.tick1line.set_markersize(3)
        tick.tick2line.set_markersize(3)
    for tick in ax.xaxis.get_major_ticks(): tick.label1.set_horizontalalignment('center')
    plt.savefig(pl.Path(out_dir,'goldbook_energy_projection.png'),bbox_inches='tight')

    ## Real NYISO Load Curve from Base Load/Weather Year (2013)
    weather_year = '2013'
    file = pl.Path(operation_nysio_dir,'{}_{}.pkl'.format(weather_year, dataset))
    load_2013 = pd.read_pickle(file).tz_convert('US/Eastern').rename(columns=nyiso_regions)
    load_2013_mwh = (load_2013/1000 * 1).sum(axis='index') # MW -> GWh
    growth_factor = df.divide(load_2013_mwh)

growth_factor[nyiso_regions.values()].to_csv(pl.Path(nysio_goldbook_dir,'load_growth_factors.
csv'))

    ## full year hourly data that we want (remove leap days)
    date_range = pd.date_range(start='{}-01-01 00:00:00'.format(infra_year),
                               end='2050-12-31 23:00:00',
                               freq='H', tz='US/Eastern').tz_convert('UTC') # all the dates that should exist
    date_range = date_range[~((date_range.month == 2) & (date_range.day == 29))] # remove leap
days
    ## Scale 2013 load [MW] to create new load 2019-2050
    frames = [load_2013.mul(row).reset_index(drop=True) for index, row in
growth_factor.iterrows()]
    future_load = pd.concat(frames)
    future_load.index = date_range

    #Plots
    fig, ax = plt.subplots(figsize=(10,5), dpi=300)
    future_load['Upstate'] = future_load[['A','B','C','D','E']].sum(axis='columns')
    future_load['Downstate'] = future_load[['F','G','H','I','J','K']].sum(axis='columns')
```

```
future_load[['NYCA','Downstate','Upstate']].resample('M').mean().plot(ax=ax, kind='line',
                                        label='Projected Hourly Load', alpha=0.8)
plt.ylabel('Power [MW]')
ax.yaxis.set_major_formatter(mat.ticker.StrMethodFormatter('{x:,.0f}'))
ax.legend(ncol=3, fancybox=True, shadow=False)
plt.xlim(future_load.index[0], future_load.index[-1])
plt.xlabel('Local Time [US/Eastern]')
#ticks

plt.xticks(df.index,rotation=0)
for tick in ax.xaxis.get_major_ticks() + ax.yaxis.get_major_ticks():
    tick.tick1line.set_markersize(3)
    tick.tick2line.set_markersize(3)
for tick in ax.xaxis.get_major_ticks(): tick.label1.set_horizontalalignment('center')
plt.ylim(0,30000)
plt.savefig(pl.Path(out_dir,'load_projection_energy.png'), bbox_inches='tight')
future_load.to_pickle(pl.Path(nysio_goldbook_dir,'2019_2050_load_energy.pkl'))
```

# Appendix V Load Scaling Factors

***Table V-1: Computed Load Growth Factors** between 2013 regional annual energy use and projected energy consumption from NYISO Goldbook 2020 Table I-6a [29]*

| Year | A | B | C | D | E | F | G | H | I | J | K | NYCA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *2019* | 0.94 | 0.97 | 0.97 | 0.75 | 0.95 | 0.98 | 0.96 | 0.94 | 0.96 | 0.98 | 0.93 | 0.95 |
| *2020* | 0.91 | 0.96 | 0.94 | 0.75 | 0.91 | 0.96 | 0.93 | 0.91 | 0.92 | 0.93 | 0.91 | 0.92 |
| *2021* | 0.92 | 0.97 | 0.95 | 0.80 | 0.92 | 0.97 | 0.94 | 0.95 | 0.91 | 0.94 | 0.92 | 0.93 |
| *2022* | 0.93 | 0.98 | 0.96 | 0.85 | 0.92 | 0.98 | 0.94 | 0.97 | 0.92 | 0.95 | 0.93 | 0.94 |
| *2023* | 0.92 | 0.98 | 0.96 | 0.88 | 0.91 | 0.97 | 0.93 | 0.98 | 0.90 | 0.93 | 0.91 | 0.93 |
| *2024* | 0.92 | 0.98 | 0.96 | 0.90 | 0.91 | 0.96 | 0.92 | 0.99 | 0.89 | 0.92 | 0.90 | 0.93 |
| *2025* | 0.91 | 0.97 | 0.96 | 0.91 | 0.90 | 0.96 | 0.91 | 0.99 | 0.89 | 0.92 | 0.89 | 0.92 |
| *2026* | 0.91 | 0.97 | 0.96 | 0.92 | 0.89 | 0.96 | 0.90 | 1.00 | 0.89 | 0.92 | 0.88 | 0.92 |
| *2027* | 0.90 | 0.97 | 0.95 | 0.93 | 0.88 | 0.95 | 0.89 | 1.00 | 0.89 | 0.92 | 0.88 | 0.92 |
| *2028* | 0.90 | 0.96 | 0.95 | 0.93 | 0.88 | 0.95 | 0.89 | 1.01 | 0.90 | 0.93 | 0.89 | 0.92 |
| *2029* | 0.89 | 0.96 | 0.95 | 0.92 | 0.87 | 0.95 | 0.89 | 1.01 | 0.90 | 0.93 | 0.90 | 0.92 |
| *2030* | 0.89 | 0.96 | 0.95 | 0.92 | 0.87 | 0.95 | 0.89 | 1.02 | 0.91 | 0.94 | 0.91 | 0.93 |
| *2031* | 0.89 | 0.96 | 0.95 | 0.92 | 0.87 | 0.95 | 0.89 | 1.03 | 0.92 | 0.95 | 0.93 | 0.93 |
| *2032* | 0.89 | 0.96 | 0.95 | 0.92 | 0.87 | 0.95 | 0.90 | 1.04 | 0.93 | 0.96 | 0.95 | 0.94 |
| *2033* | 0.89 | 0.97 | 0.95 | 0.92 | 0.87 | 0.95 | 0.91 | 1.05 | 0.94 | 0.97 | 0.97 | 0.95 |
| *2034* | 0.89 | 0.97 | 0.95 | 0.92 | 0.88 | 0.96 | 0.92 | 1.06 | 0.96 | 0.99 | 1.00 | 0.96 |
| *2035* | 0.90 | 0.98 | 0.96 | 0.93 | 0.88 | 0.96 | 0.93 | 1.07 | 0.97 | 1.01 | 1.03 | 0.97 |
| *2036* | 0.90 | 0.99 | 0.96 | 0.93 | 0.88 | 0.97 | 0.95 | 1.08 | 0.99 | 1.02 | 1.06 | 0.99 |
| *2037* | 0.91 | 1.00 | 0.97 | 0.93 | 0.89 | 0.98 | 0.96 | 1.09 | 1.01 | 1.04 | 1.10 | 1.00 |
| *2038* | 0.91 | 1.01 | 0.98 | 0.94 | 0.90 | 0.98 | 0.97 | 1.11 | 1.02 | 1.06 | 1.13 | 1.02 |
| *2039* | 0.92 | 1.02 | 0.98 | 0.94 | 0.90 | 0.99 | 0.99 | 1.12 | 1.04 | 1.07 | 1.17 | 1.03 |
| *2040* | 0.93 | 1.03 | 0.99 | 0.95 | 0.91 | 1.00 | 1.01 | 1.13 | 1.05 | 1.09 | 1.19 | 1.05 |
| *2041* | 0.94 | 1.04 | 1.00 | 0.95 | 0.92 | 1.01 | 1.02 | 1.14 | 1.07 | 1.10 | 1.20 | 1.06 |
| *2042* | 0.94 | 1.05 | 1.01 | 0.95 | 0.93 | 1.01 | 1.04 | 1.15 | 1.08 | 1.12 | 1.22 | 1.07 |
| *2043* | 0.95 | 1.07 | 1.01 | 0.96 | 0.93 | 1.02 | 1.06 | 1.16 | 1.10 | 1.13 | 1.23 | 1.08 |
| *2044* | 0.96 | 1.08 | 1.02 | 0.96 | 0.94 | 1.03 | 1.07 | 1.16 | 1.11 | 1.14 | 1.25 | 1.09 |
| *2045* | 0.97 | 1.09 | 1.03 | 0.96 | 0.95 | 1.04 | 1.09 | 1.17 | 1.12 | 1.16 | 1.26 | 1.10 |
| *2046* | 0.98 | 1.10 | 1.03 | 0.96 | 0.96 | 1.04 | 1.10 | 1.17 | 1.13 | 1.16 | 1.27 | 1.11 |
| *2047* | 0.98 | 1.11 | 1.04 | 0.97 | 0.96 | 1.05 | 1.12 | 1.18 | 1.14 | 1.17 | 1.28 | 1.12 |
| *2048* | 0.99 | 1.11 | 1.04 | 0.97 | 0.97 | 1.06 | 1.13 | 1.18 | 1.14 | 1.18 | 1.30 | 1.13 |
| *2049* | 1.00 | 1.12 | 1.05 | 0.97 | 0.98 | 1.06 | 1.15 | 1.18 | 1.15 | 1.18 | 1.31 | 1.13 |
| *2050* | 1.00 | 1.13 | 1.05 | 0.97 | 0.98 | 1.07 | 1.16 | 1.19 | 1.15 | 1.19 | 1.32 | 1.14 |

# Appendix VI Average Heat Rates

***Table VI-1: EIA860 Table 8.2. Average Tested Heat Rates [Btu/KWh] by Prime Mover and Energy Source (2018)*** *[30]*

| Prime Mover | Coal | Petroleum | Natural Gas | Nuclear |
|---|---|---|---|---|
| *Steam Generator* | 10,015 | 10,270 | 10,334 | 10,455 |
| *Gas Turbine* | -- | 13,352 | 11,138 | -- |
| *Internal Combustion* | -- | 10,326 | 9,009 | -- |
| *Combined Cycle* | W | 9,663 | 7,627 | -- |

# Appendix VII Technical Resource Group and Capacity Factor Mapping

***Table VII-1: NREL 2019 ATB Technical Resource Group to Capacity Factor Mapping for 2019 Mid-Case Cost Scenario*** *[26]*

| Offshore Tech Detail | Capacity Factor |
|---|---|
| *OTRG1* | 45% |
| *OTRG2* | 44% |
| *OTRG3* | 44% |
| *OTRG4* | 41% |
| *OTRG5* | 30% |
| *OTRG6* | 52% |
| *OTRG7* | 51% |
| *OTRG8* | 50% |
| *OTRG9* | 49% |
| *OTRG10* | 48% |
| *OTRG11* | 43% |
| *OTRG12* | 37% |
| *OTRG13* | 34% |
| *OTRG14* | 31% |
| *OTRG15* | 28% |

| Onshore Tech Detail | Capacity Factor |
|---|---|
| *LTRG1* | 49% |
| *LTRG2* | 46% |
| *LTRG3* | 45% |
| *LTRG4* | 44% |
| *LTRG5* | 41% |
| *LTRG6* | 36% |
| *LTRG7* | 30% |
| *LTRG8* | 24% |
| *LTRG9* | 17% |
| *LTRG10* | 11% |

# Appendix VIII A Detailed Look at Modeled Curtailment

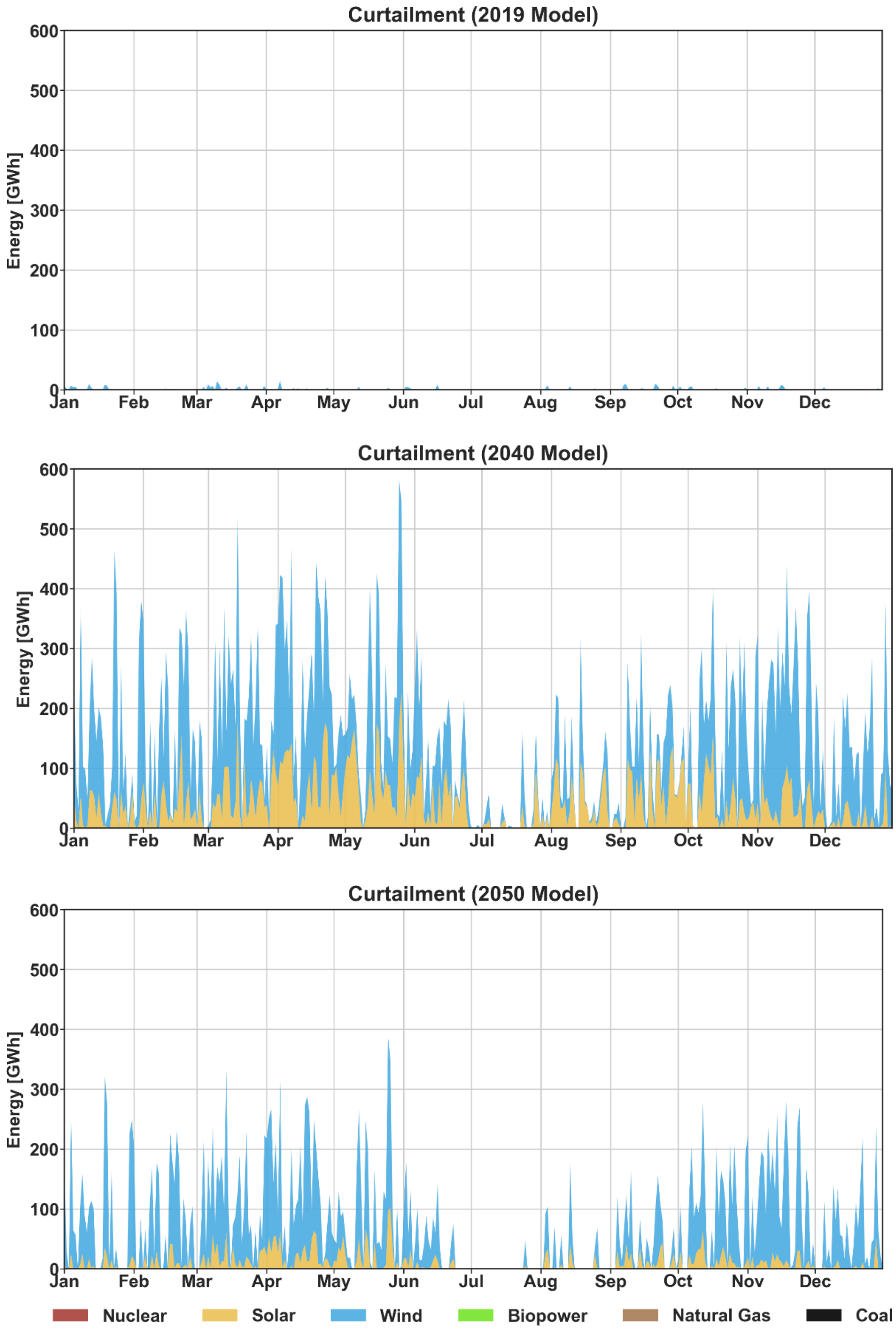


***Figure VIII-1: Daily Energy Curtailment.*** *Note: Only Hydro, Wind, and Solar resources had curtailed.*

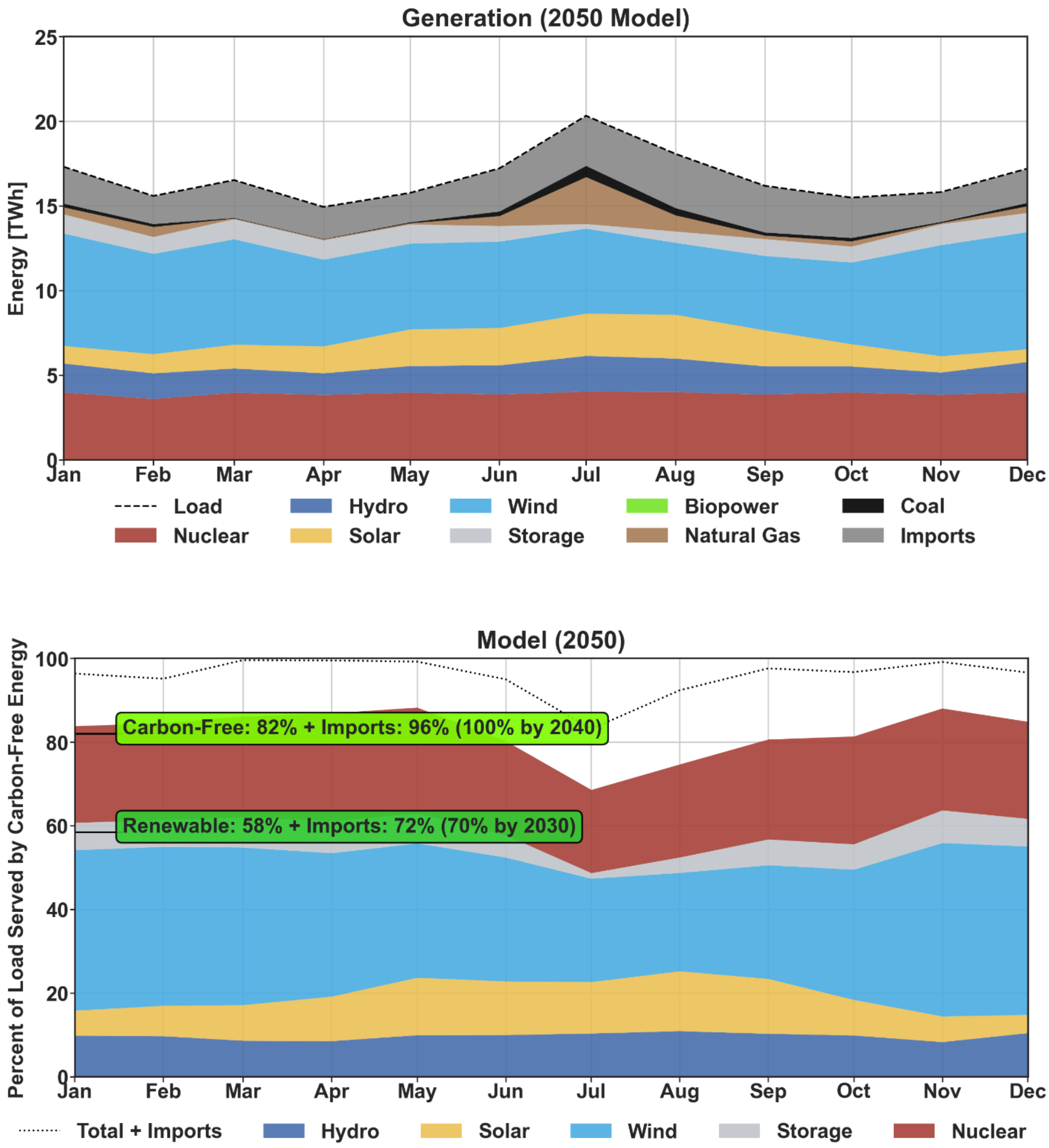


***Figure IX-1: 2050 Modeled Seasonal Variation in Monthly Energy Generation and Carbon-Free Operation.*** *The dotted line shows the level of carbon-free energy which served load if all the imported energy procured by utilities from out of state came from carbon-free sources. Figure inspired by NYISO Power Trends 2020 [28].*

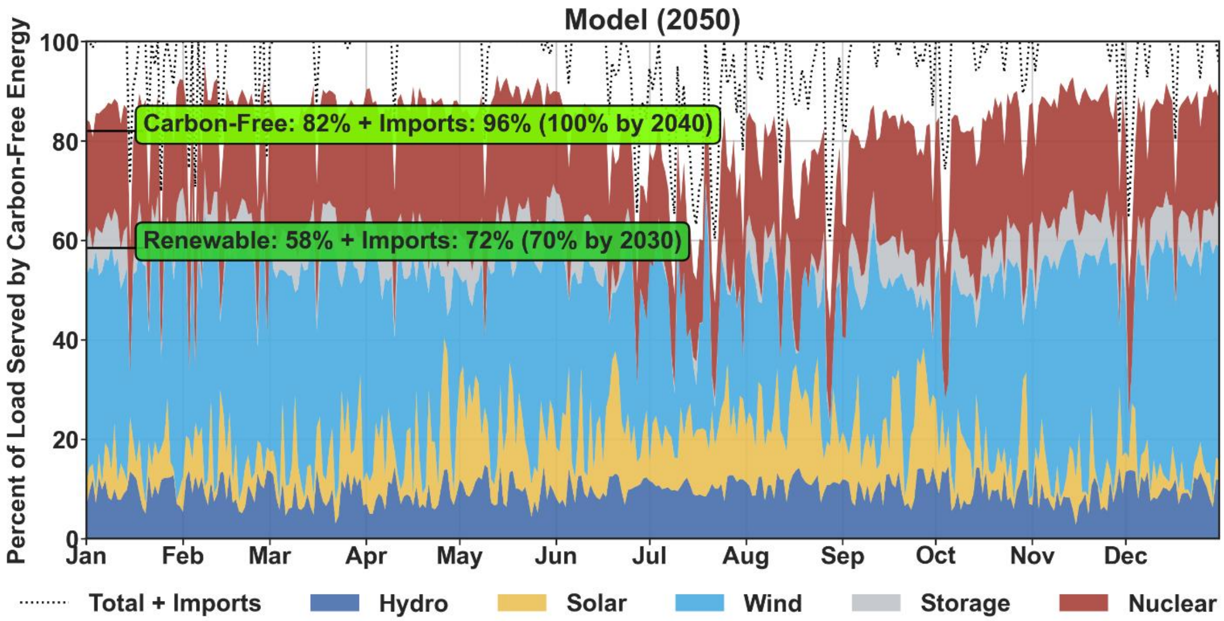


*Figure IX-2: Modeled 2050 Carbon-Free Daily Operation*

## Appendix X 2040 and 2050 Daily Energy Generation

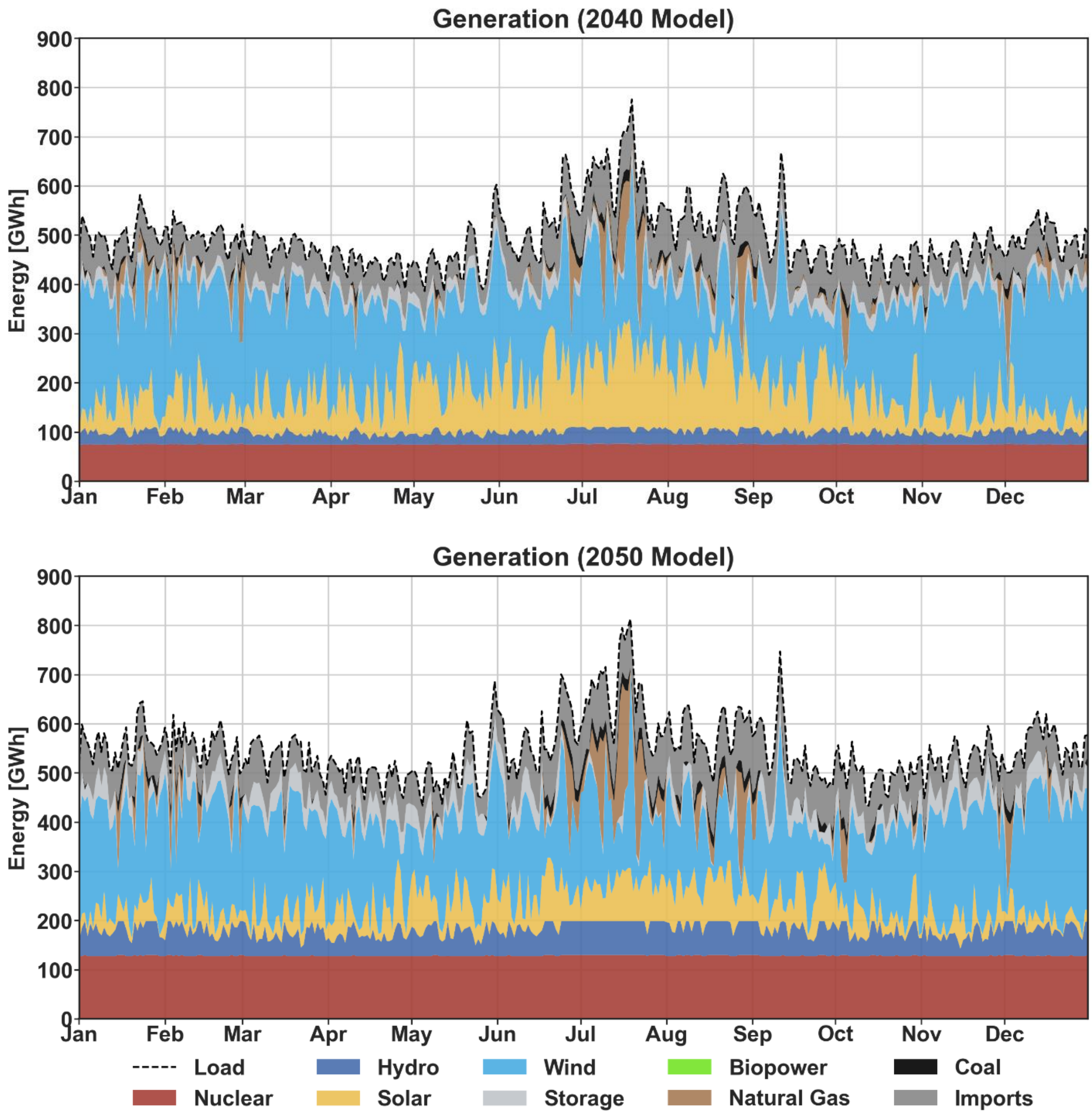


*Figure X-1: Modeled 2040 and 2050 Daily Energy Generation by Generator Technology.*

## Appendix XI Seasonal Operation of Battery Storage

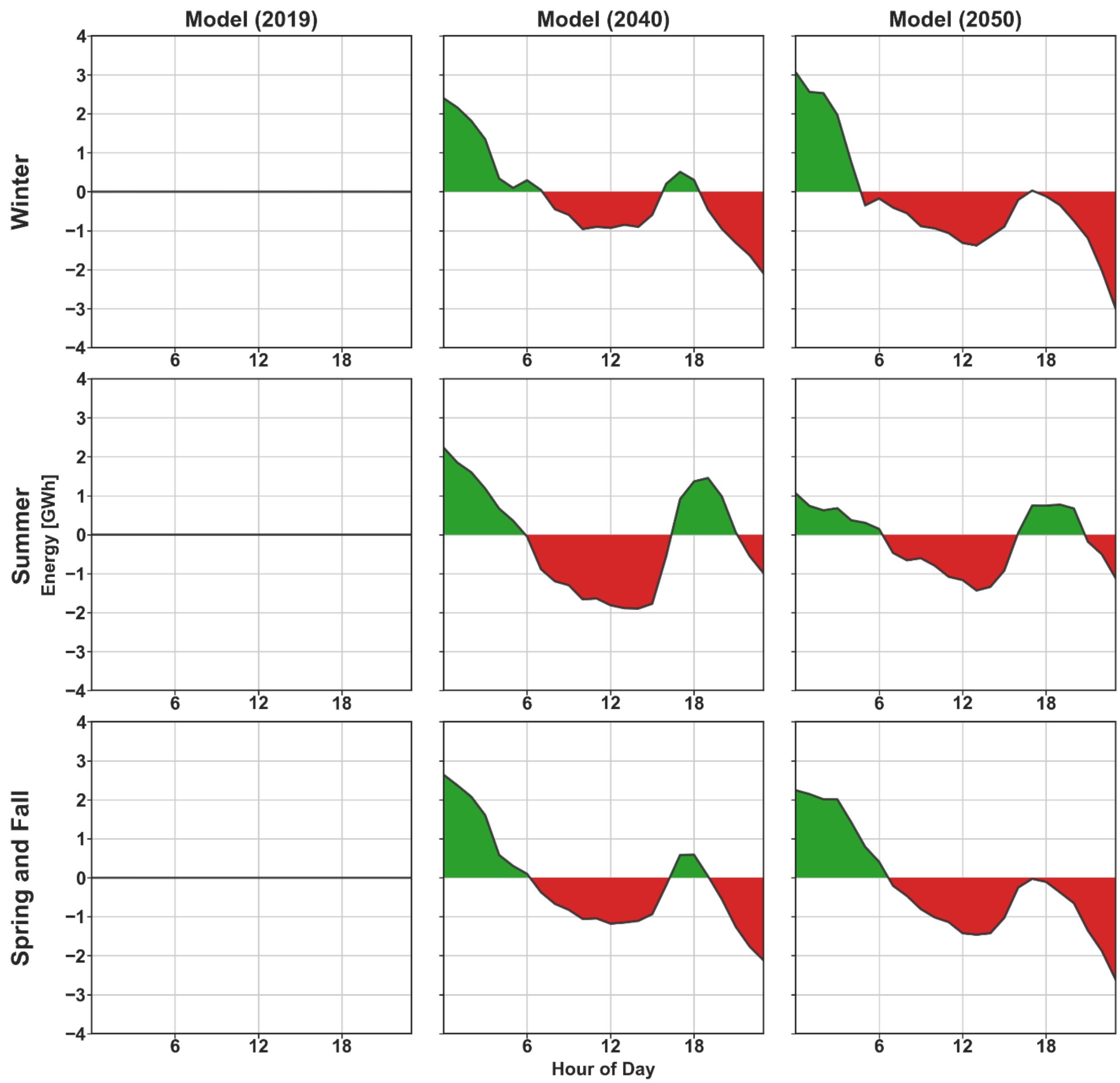


*Figure XI-1: Seasonal Operation of Battery Storage*

# Appendix XII Wind Ramping Events

*Table XII-1: Top Wind Ramping Events (2019)*

| Datetime | Wind Delta [GWh] | Ramp Length (Hours) | Normalized Wind Delta [GWh] |
|---|---|---|---|
| **2019-03-10 15:00:00-04:00** | 1.919976 | 10 | 1.919976 |
| **2019-03-10 15:00:00-04:00** | 1.914431 | 15 | 1.914431 |
| **2019-01-07 09:00:00-05:00** | 1.904112 | 11 | 1.904112 |
| **2019-02-12 13:00:00-05:00** | -1.90236 | 24 | 1.902362 |
| **2019-08-07 22:00:00-04:00** | -1.90106 | 19 | 1.901065 |

*Table XII-2: Top Wind Ramping Events (2040)*

| Datetime | Wind Delta [GWh] | Ramp Length (Hours) | Normalized Wind Delta [GWh] |
|---|---|---|---|
| **2040-05-31 07:00:00-05:00** | 20.82621 | 13 | 20.82621 |
| **2040-05-31 07:00:00-05:00** | 20.6394 | 12 | 20.6394 |
| **2040-05-31 09:00:00-05:00** | 20.18217 | 11 | 20.18217 |
| **2040-05-31 09:00:00-05:00** | 19.99536 | 10 | 19.99536 |
| **2040-09-11 08:00:00-05:00** | 19.98687 | 11 | 19.98687 |

*Table XII-3: Top Wind Ramping Events (2050)*

| Datetime | Wind Delta [GWh] | Ramp Length (Hours) | Normalized Wind Delta [GWh] |
|---|---|---|---|
| **2050-11-10 19:00:00-05:00** | -22.1145 | 7 | 22.1145 |
| **2050-11-10 03:00:00-05:00** | 22.1145 | 16 | 22.1145 |
| **2050-01-30 20:00:00-05:00** | -21.6957 | 4 | 21.69566 |
| **2050-01-30 00:00:00-05:00** | 21.69566 | 20 | 21.69566 |
| **2050-01-30 02:00:00-05:00** | 21.69566 | 18 | 21.69566 |

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