Assessing Policies to Incentivize End-Use Clean Energy Adoption

Demonstrative Results

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Objective

Roughly a dozen states are aspiring to achieve zero net GHG emissions for their economy by 2050. In most of those (and all parts of the country), the share of CO_2e that comes from power plants is at or below 25%, with the large majority coming from transportation, agriculture, and residential and commercial end-use of fossil fuels for heating and manufacturing. The latter are all unregulated sectors for which we have no direct mechanisms for influencing their energy use decisions. Yet, if they do not decarbonize their end-uses, we cannot achieve even a fraction of 2050 aspirations, even if the power sector were to be entirely carbon-free.

New incentives, subsidies, mandates, or penalties will be necessary to induce the needed end-use changes. Many states desiring decarbonization have not evaluated the economic impacts or tradeoffs between these enforcement approaches. Carbon pricing is often described as the ideal mechanism, but its application to date has either been fairly narrowly restricted to power and just a few other sectors, and/or it has not been allowed to reach price levels commensurate with technology substitution economics (nor with typical estimates of the social cost of carbon). Thus, it is unproven at best.

In this report, we examine whether (and in what ways) the design of a carbon tax could induce end-use changes to achieve material decarbonization, and what pattern of economic impacts that would have on different sectors of a regional economy, under consistent assumptions about electric system requirements. Further, we review how revenue recycling from such taxes could be targeted to reduce adverse impacts on key groups such as critical industries or low-income customers.

Approach

We deploy two parallel models to capture how carbon prices could alter energy use patterns and the economic conditions of the overall state economy:

1. Brattle's **BEYOND** Competitive General Equilibrium (CGE) model of the US economy
2. Brattle's **gridSIM** model of power market dispatch and capacity expansion under typical power system operating constraints (for reliability, demand balance, ancillary services, line flow capacities, etc.).

The two models are linked and iterated to converge on concurrent feasibility and pricing for energy use and economic needs. (Details about the models are in the appendix.)

We study a simplified representation of NY state system over a 25-year horizon (thru 2050). *The analysis is not meant to be a policy assessment of or for the state, but rather a demonstration of how carbon pricing (not in effect in NY) could help achieve climate protection goals in a way that allows tradeoffs across economic development and economic impact goals for sectors of the regional economy.*

We model **reference conditions (BAU)** with some existing carbon reduction mandate policies in effect and **several policy-design scenarios** to assess:

- Impacts of alternative carbon price trajectories;
- Alternative revenue recycling strategies; and
- One scenario with a very tight hard cap-and-trade limit on allowable emissions.

These allow us to compare economic impacts over time (on GDP, employment, sectoral output, power system needs, energy burdens) and across sectors, and to show how revenue recycling can mitigate some adverse impacts.

NY CO_2 Emissions (2023, MMT CO_2)

Total CO_2 Emissions by Sector (165.5 MMT Net CO_2)

Transportation: 77.6 MMT, 46.9%

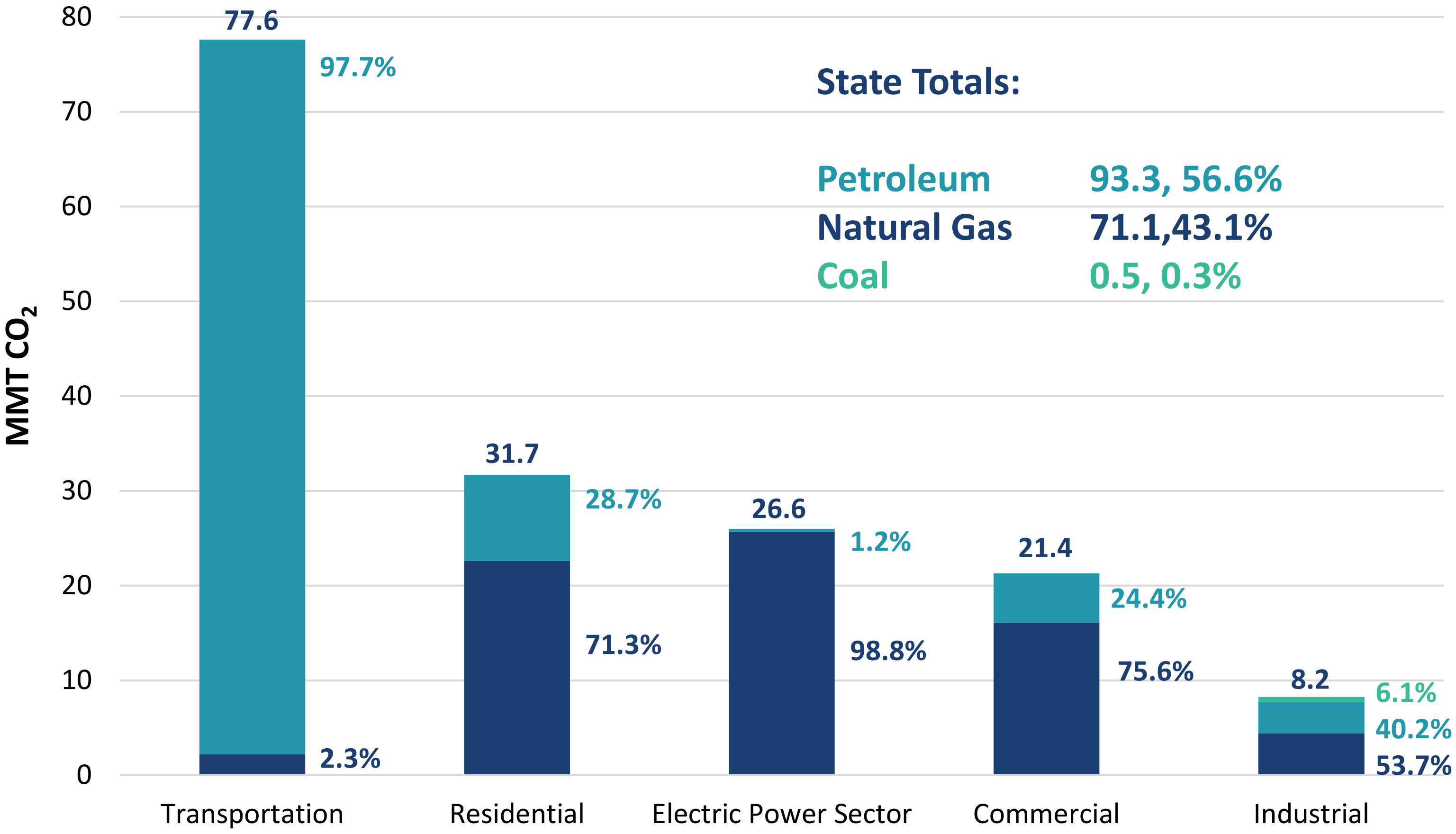
Residential: 31.7 MMT, 19.2%

Electric Power Sector: 26.6 MMT, 16%

Commercial: 21.4 MMT, 12.9%

Industrial: 8.2, 5%

Emissions by Fuel Type

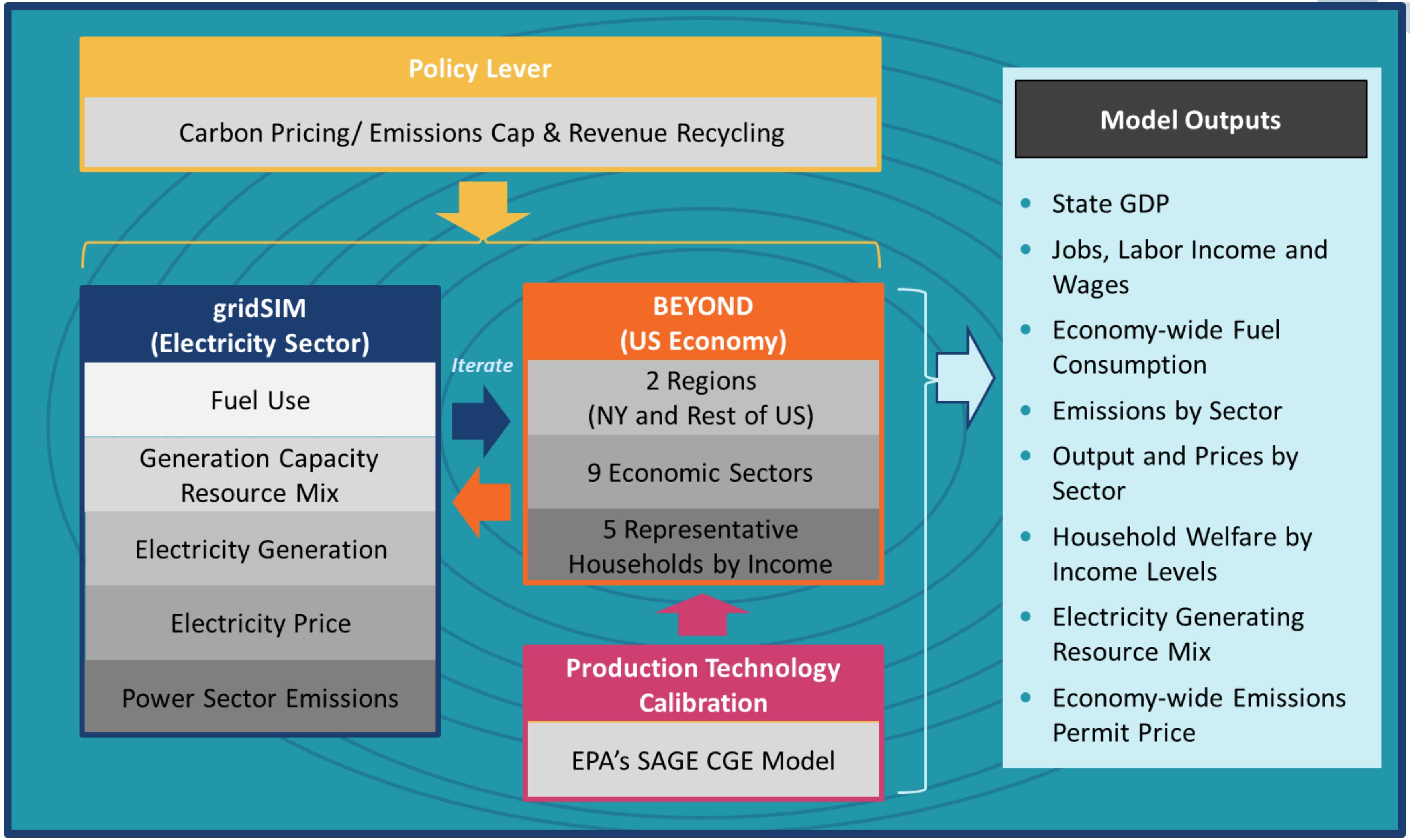


Source: EIA State Energy Data System (SEDS)

Integrated Modeling Framework: gridSIM and BEYOND

Brattle's analysis uses an integrated modeling framework that couples two proprietary models:

- **BEYOND:**
  A dynamic general equilibrium model of the US economy that simulates key interactions between industries, households, and government.
- **gridSIM:**
  A detailed electricity sector model that optimizes long-term generation and transmission capacity expansion and simulates hourly market operations and resulting costs for consistency with macro conditions.

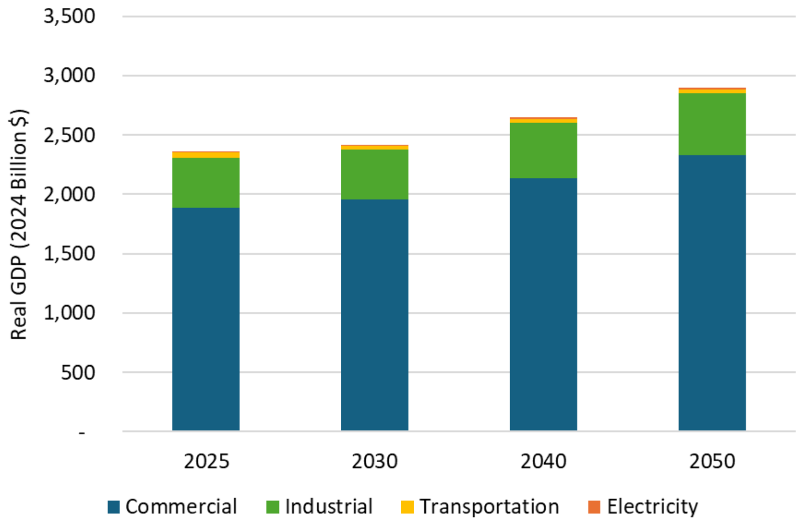


Reference (BAU) Outlook: GDP and Emissions

We simulate NY state with its participation in NYISO and the adjacent regional power markets along with its macroeconomic interactions with the rest of the US. NY is subject to legislative mandates for some specific GHG emission reductions, and broader goals for full decarbonization by 2050.

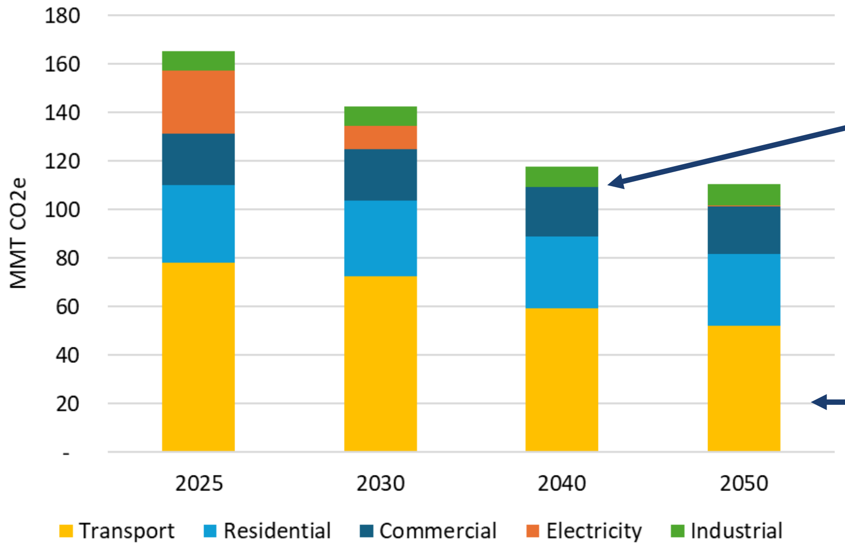
- BAU conditions under NY law (CLCPA) require the electric sector to fully decarbonize by 2040 along with some mandated adjustments to a few other sectors, especially transportation.
- However, these will only reduce current carbon emissions by about 1/3. Other incentives or mandates (e.g., GHG pricing, tested herein) will be required to achieve deeper decarbonization.

BAU Real GDP and Value-Added by Sector



Real GDP grows by ~2%/year on average based on State's projections

Emissions by End Use



Electricity mandated to be clean by 2040, regardless of other policies

Transportation falls due to NY's transportation emissions policies (e.g.,NY *Clean Car Act*)

Carbon Pricing and Emissions Capping Scenarios

These scenarios evaluate the extent to which CO_2 emissions pricing can induce decarbonization of the unregulated sectors of the NY economy. Revenues are recycled variously to study sectoral impacts. No new mandatory "complementary measures" or incentives (tax credits, direct subsidies) are evaluated.

Scenario	CO2 prices* 2030/2040/2050	Excluded sectors	Revenue Recycling	Emissions Cap	Positive Learning Feedback in Electrification
A	100/200/300	Air Transport	Household Dividends (100%)	No	No
B	200/300/400	Air Transport	Household Dividends (100%)	No	No
B-Invest	200/300/400	Air Transport	Households Dividends (30%) Climate Investments (70%) - 30% to Transportation - 70% to Commercial/Residential Buildings	No	No
B-Learn	200/300/400	Air Transport	Households Dividends (30%) Climate Investments (70%) - 30% to Transportation - 70% to Commercial/Residential Buildings	No	Yes
C	N/A	Air Transport	Households Dividends (30%) Climate Investments (70%) - 30% to Transportation - 70% to Commercial/Residential Buildings	40%, 60%, 80% Reduction Relative to Reference Emissions in 2030, 2040, 2050	Yes

By comparison to public policies in place today, *fairly high CO_2 prices are tested.*

- These are set at these levels because studies of clean technology substitution at end-use often find high costs of carbon abatement and because the social cost of carbon is often estimated to be in the $100–300/ton or greater range.

The appendix presents information on ranges of costs of carbon avoidance by decarb technology.

Scenario A: Gradual CO_2 Pricing ($100–200–300) on All Sectors

A gradual CO_2 price increase induces a material change in emissions but does not satisfy CLCPA goals. At $300/ton by 2050, price signals eliminate 33% of BAU emissions, or down to about 45% of 2025 levels.

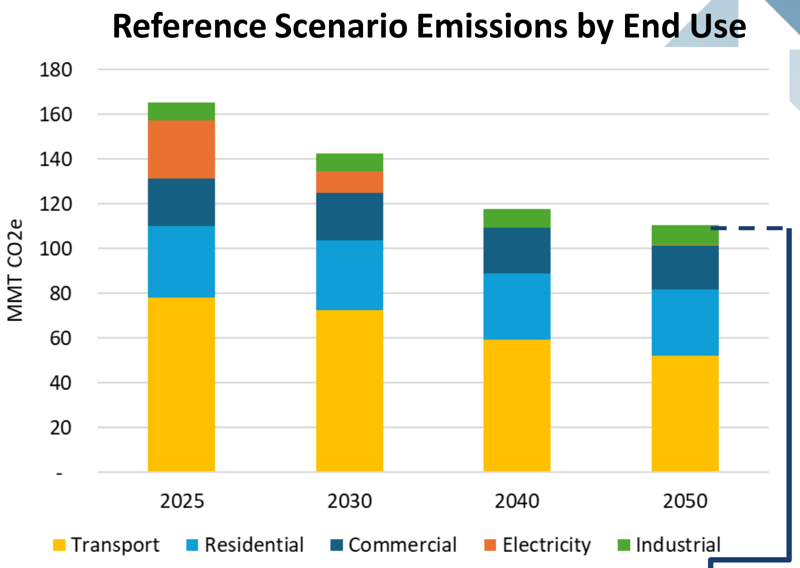
Relative to Reference Scenario	2030	2040	2050
% Change in Total Emissions	-13%	-25%	-33%
% Change in Real GDP	-0.9%	-1.9%	-2.8%
Permit Price ($/ton)	$100	$200	$300
Annual CO2 Revenue ($2024 Billion)	$12.8	$23.3	$34.9
% Change in Energy Wallet: *Low Income Households*	0.3%	0.8%	1.1%
% Change in Energy Wallet: *High Income Households*	0.0%	0.0%	0.1%
% Change in Employment	-0.9%	-1.9%	-2.9%
% Change in Electricity Price	0.9%	5.3%	7.4%
% Change in Annual Total Electricity Demand	0.7%	3.7%	5.0%

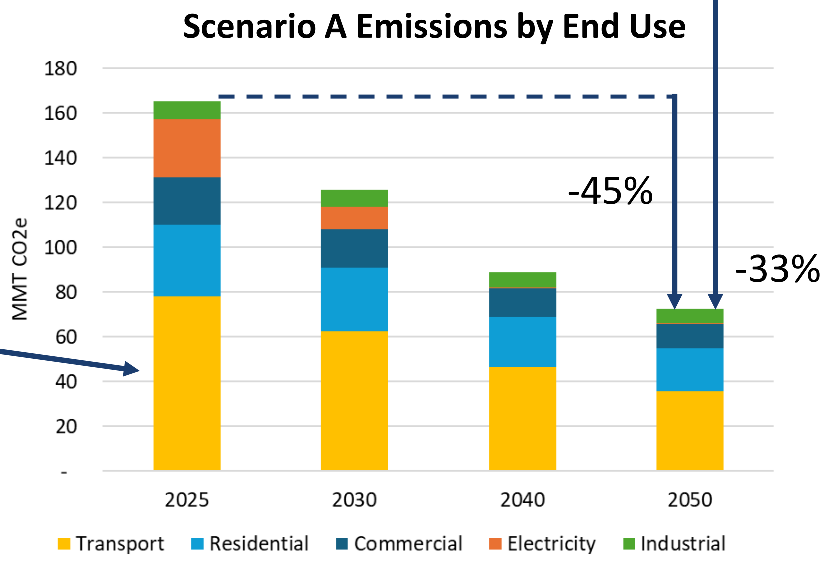
In 2050, approximately $79B of reduced real GDP, or about $4400/capita.

Emissions revenues reach roughly 40% of current out-of-pocket costs for energy consumption, but revs are fully recycled to households.

Transportation emissions fall more than other sectors.

Electricity prices and demand rise due to substitution away from fossil fuels.





Scenario A: Importance of Electricity Sector Modeling

Top-down representations of electricity in CGE models do not realistically capture the costs of meeting increased electricity demand with resource adequacy. BEYOND estimates the annual electricity demand in NY, then Brattle's gridSIM model is used to estimate system costs and electricity prices from generation capacity expansion and dispatch.

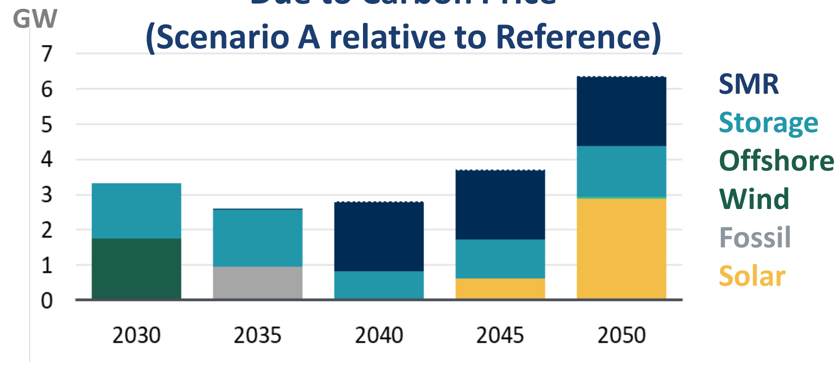
Relative to Reference Scenario	2050 NO Electricity Model	2050 YES Electricity Model
% Change in Total Emissions	-34%	-33%
% Change in Real GDP	-2.7%	-2.8%
Permit Price ($/ton)	$300	$300
Annual CO2 Revenue ($2024 Billion)	$34.9	$34.9
% Change in Energy Wallet: *Low Income Households*	1.1%	1.1%
% Change in Energy Wallet: *High Income Households*	0.0%	0.1%
% Change in Employment	-2.8%	-2.9%
% Change in Electricity Price	1.5%	7.4%
% Change in Annual Total Electricity Demand	8.5%	5.0%

Cost of higher load is underestimated in BEYOND. A 5% increase in annual total load also results in 5% higher requirements in RPS and clean energy generation targets.

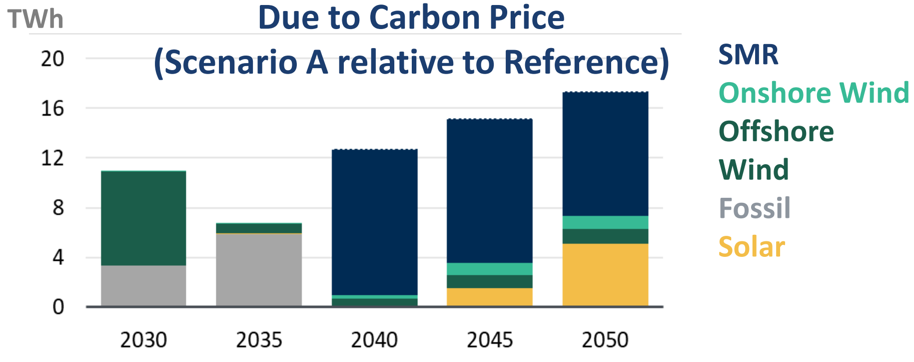
Higher peak load will incentivize more storage and dispatchable emissions free resources as well as higher demand side resource penetration.

Not accounting for such grid investment dynamics in BEYOND can result in lower electricity sector costs and in turn, inflated economy-wide power demand; gridSIM corrects this.

Peak Capacity Additions Due to Carbon Price (Scenario A relative to Reference)



Annual Generation Growth Due to Carbon Price (Scenario A relative to Reference)



Scenario B: Aggressive CO_2 Pricing ($200–300–400)

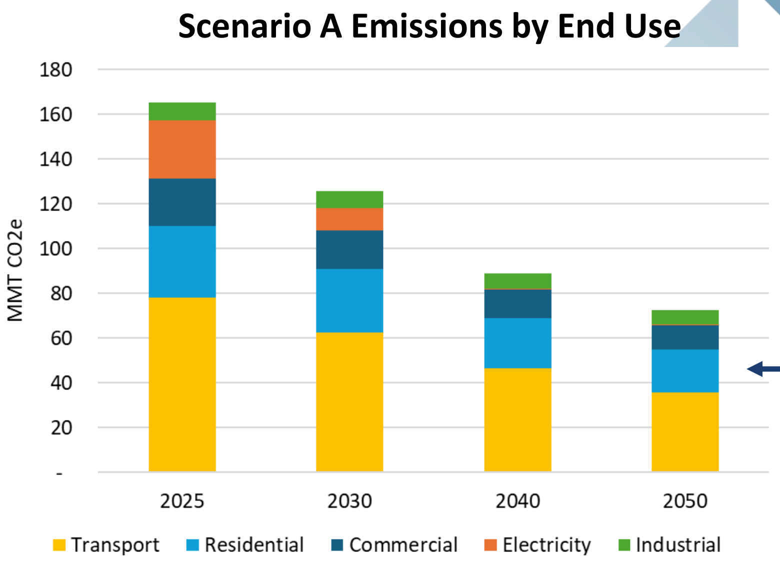
A higher and growing CO_2 price ($200–300–400) induces earlier and greater emissions' reductions but at the cost of employment and GDP growth. Emissions reduction by 2050 reaches -43% of BAU for that year.

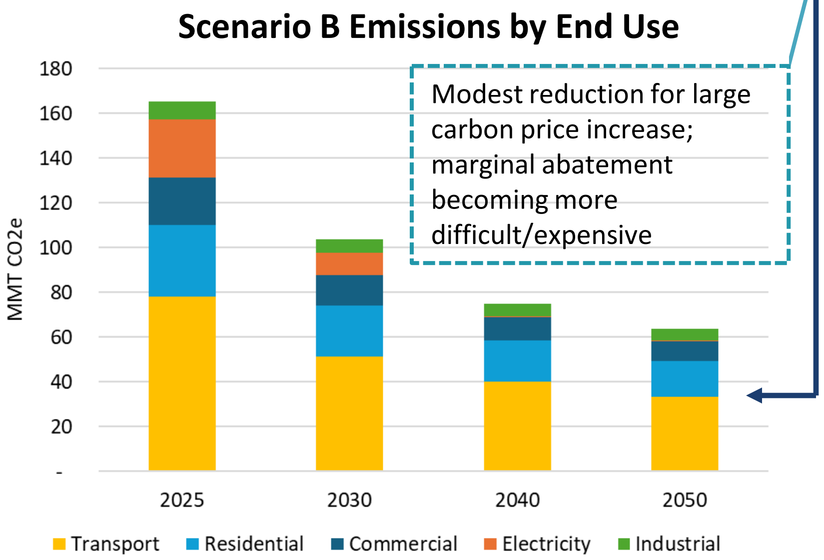
Relative to Reference Scenario	2030	2040	2050
% Change in Total Emissions	-29%	-37%	-43%
% Change in Real GDP	-2.1%	-2.7%	-3.6%
Permit Price ($/ton)	$200	$300	$400
Annual CO2 Revenue ($2024 Billion)	$20.7	$29.1	$39.7
% Change in Energy Wallet: *Low Income Households*	0.8%	1.0%	1.7%
% Change in Energy Wallet: *High Income Households*	0.0%	0.0%	0.3%
% Change in Employment	-2.1%	-2.8%	-3.8%
% Change in Electricity Price	8.3%	8.8%	11.6%
% Change in Annual Total Electricity Demand	4.5%	5.2%	7.1%

In 2050, about $100B of reduced real GDP.

Emissions revenues in 2050 are about 25% of current state operating budget.

Electricity demand and prices rise as economy undergoes higher levels of electrification.





Scenario B-Invest: Allocating Revenue to Clean Investments

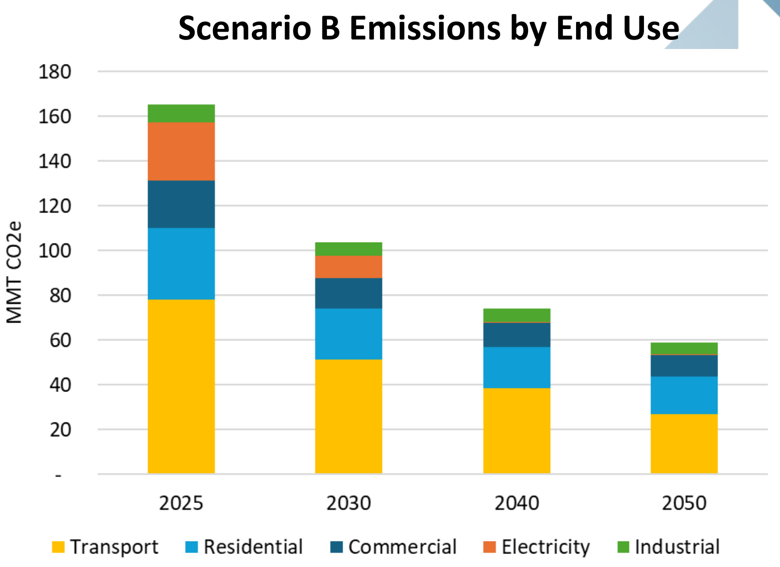
Allocating 70% of emissions revenue to clean investments in the transport and buildings sectors alleviates a portion of NY's abatement costs, incentivizing earlier and more emissions reduction. Allocation can be tuned to protect the welfare economically critical or politically sensitive sectors.

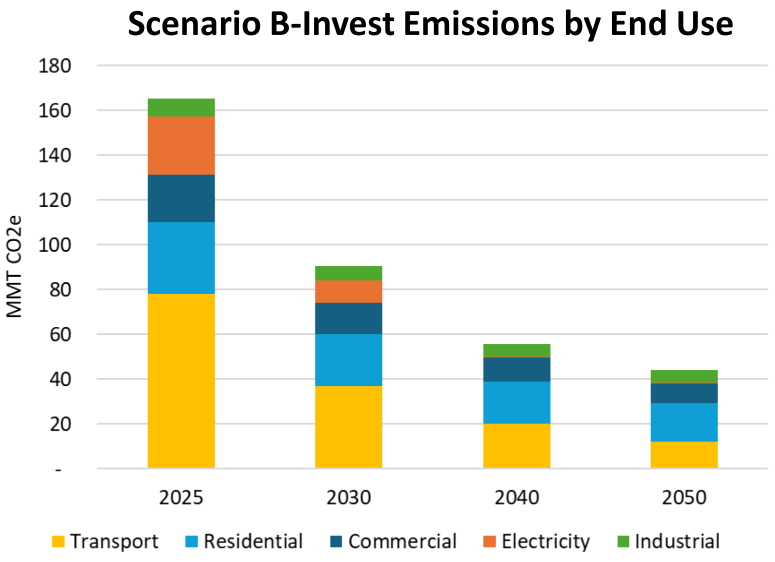
Relative to Reference Scenario	2030	2040	2050
% Change in Total Emissions	-38%	-51%	-58%
% Change in Real GDP	-2.3%	-2.9%	-3.7%
Permit Price ($/ton)	$200	$300	$400
Annual CO2 Revenue ($2024 Billion)	$18.3	$22.8	$29.5
% Change in Energy Wallet: *Low Income Households*	0.6%	0.7%	1.1%
% Change in Energy Wallet: *High Income Households*	0.2%	0.2%	0.4%
% Change in Employment	-1.6%	-2.0%	-2.7%
% Change in Electricity Price	25.0%	26.2%	39.6%
% Change in Annual Total Electricity Demand	15.0%	21.7%	21.6%

30% more emission reductions than prior *Scenario B* (where revenue 100% returned as household dividends), but GDP is almost same – i.e., effects of *more* production in clean sectors moderated by *less* consumption due to lower household dividends.

As clean sector production is subsidized, more inputs (including labor) are consumed.

Electricity demand rises by more than 20% of 2050 reference levels as economy electrifies





Scenario B-Learn: Learning-by-Doing in Clean Tech Adoption

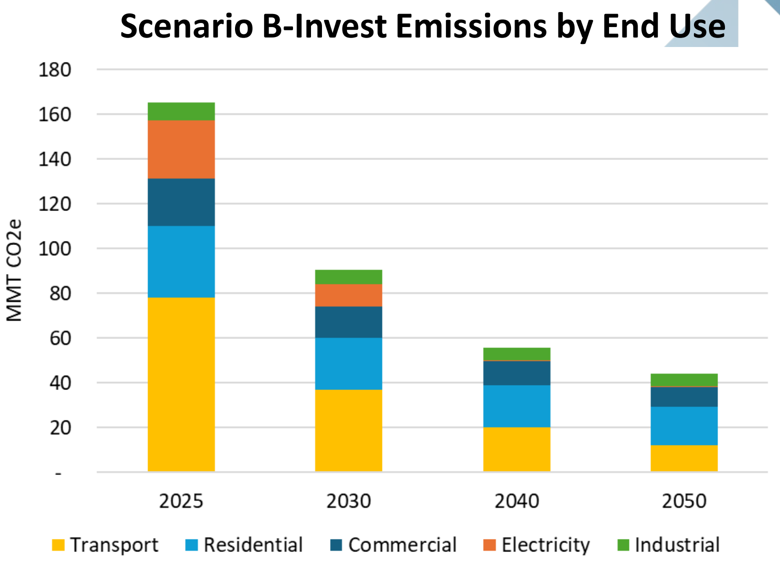
Improved costs and performance of clean technologies lowers their future adoption costs. Simulating such Learning-by-Doing (LBD) accelerates economy-wide decarbonization and alleviates welfare and GDP impacts.

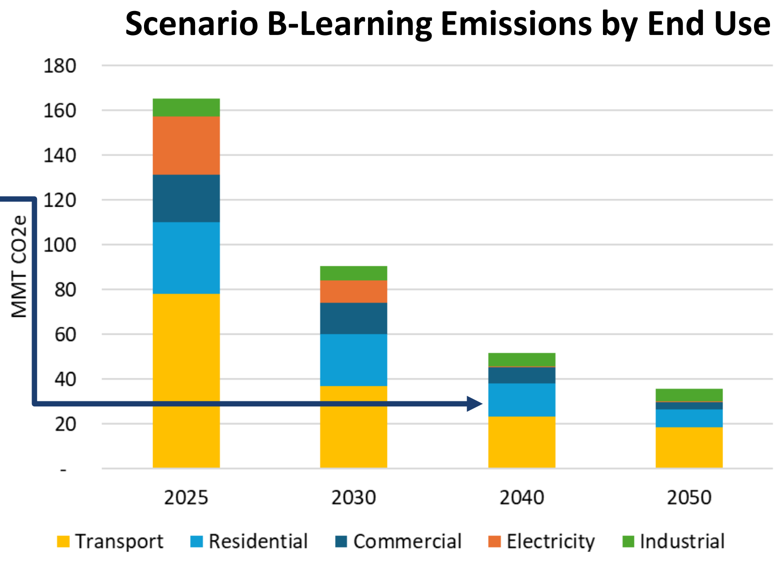
Relative to Reference Scenario	2030	2040	2050
% Change in Total Emissions	-38%	-56%	-68%
% Change in Real GDP	-2.3%	-2.5%	-2.6%
Permit Price ($/ton)	$200	$300	$400
Annual CO2 Revenue ($2024 Billion)	$18.3	$20.5	$22.3
% Change in Energy Wallet: *Low Income Households*	0.6%	0.7%	0.8%
% Change in Energy Wallet: *High Income Households*	0.2%	0.1%	0.0%
% Change in Employment	-1.6%	-1.9%	-2.1%
% Change in Electricity Price	25.0%	28.9%	39.3%
% Change in Annual Total Electricity Demand	15.0%	24.1%	27.7%

*Assuming 15% cost reduction per doubling in technology adoption** lowers emissions, GDP, employment, and welfare impacts compared to the previous scenario that does not assume learning.

More emissions reductions in buildings driven by learning.

Electricity demand rises further, but the increase in electricity production costs is partially offset by more cost-efficient production through learning in the rest of the economy .





* Jacoby, Henry D., et al. "Technology and technical change in the MIT EPPA model." Energy Economics 28.5-6 (2006): 610-631.

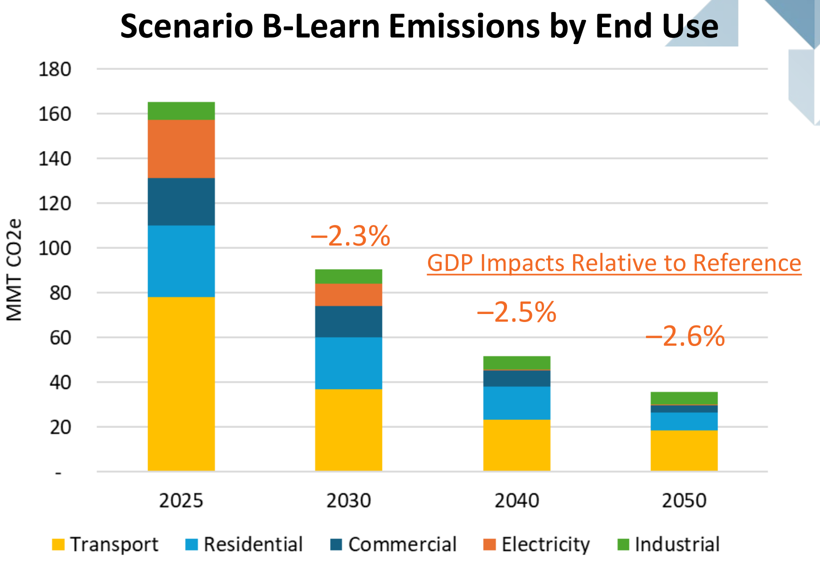
Scenario C: Emissions Cap (40-60-80% Reduction from Reference)

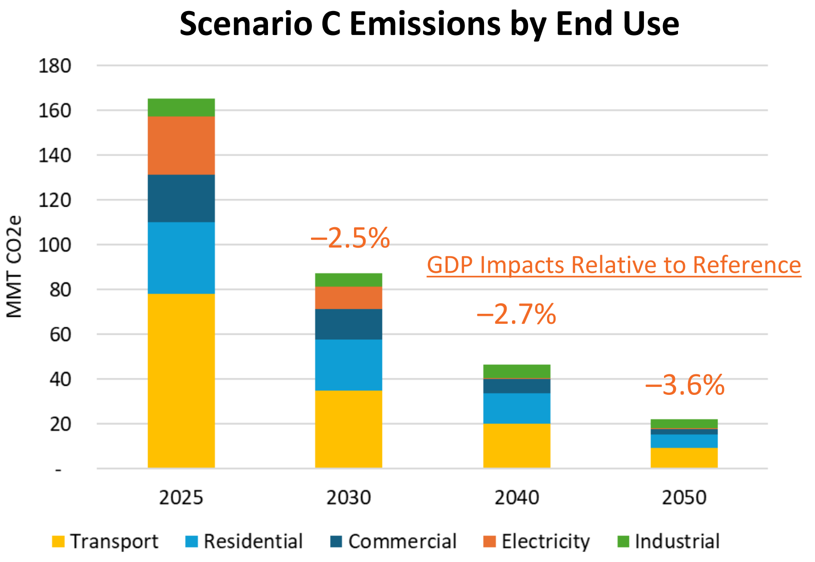
Here, *emission prices are endogenous* (policy shadow prices). A cap on emissions at 80% below reference levels in 2050 drives the permit price to \$630/ton. Learning-by-doing and revenue investment in clean tech makes 80% reduction achievable.

Relative to Reference Scenario	2030	2040	2050
% Change in Total Emissions	-40%	-60%	-80%
% Change in Real GDP	-2.5%	-2.7%	-3.6%
Permit Price (\$/ton)	\$216	\$340	\$629
Annual CO2 Revenue (\$2024 Billion)	\$19.0	\$21.0	\$21.8
% Change in Energy Wallet: *Low Income Households*	0.7%	0.7%	1.4%
% Change in Energy Wallet: *High Income Households*	0.2%	0.1%	0.3%
% Change in Employment	-1.6%	-1.8%	-3.0%
% Change in Electricity Price	27.5%	33.2%	55.3%
% Change in Annual Total Electricity Demand	15.7%	25.8%	32.0%

Learning-by-doing in technology adoption is important in keeping economic costs low in more aggressive decarbonization policies.

80% emissions reduction achieved at similar economic costs (GDP, employment) as in **Scenario B-Invest**, where learning does not result in cost efficiencies and emissions are reduced only by ~60% compared to reference levels in 2050.

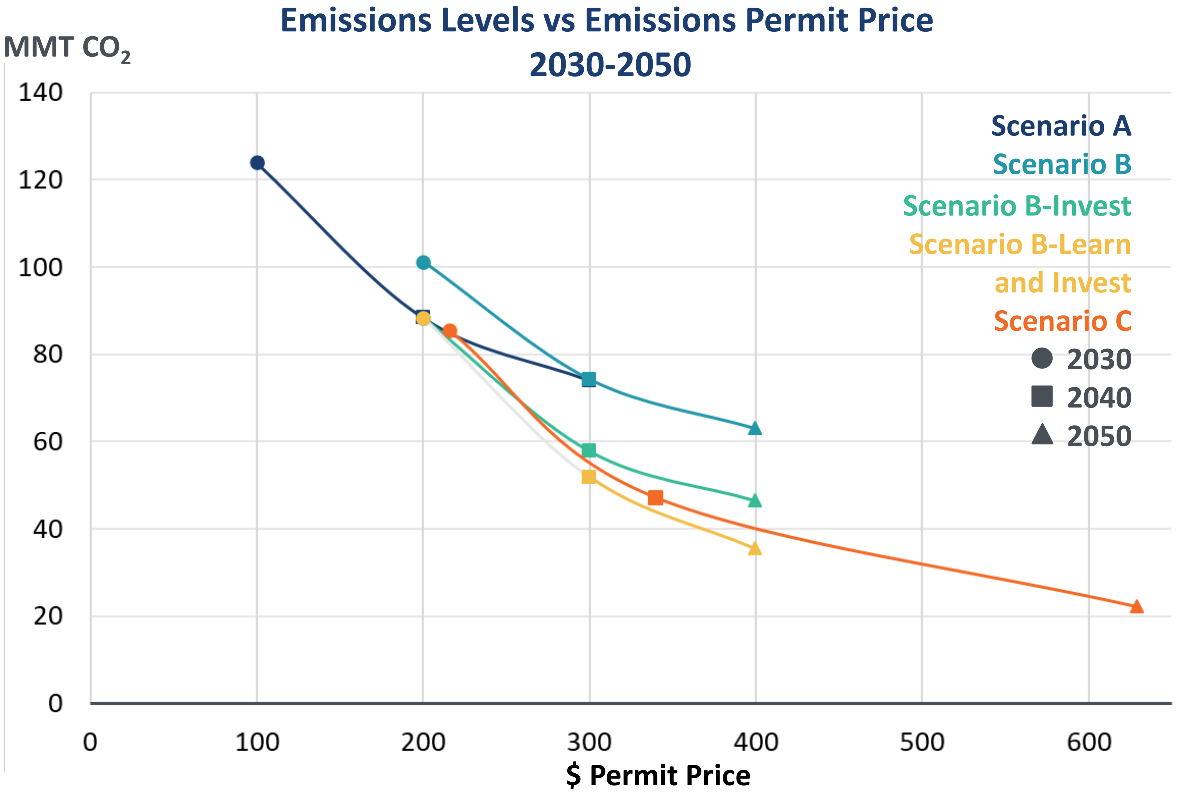


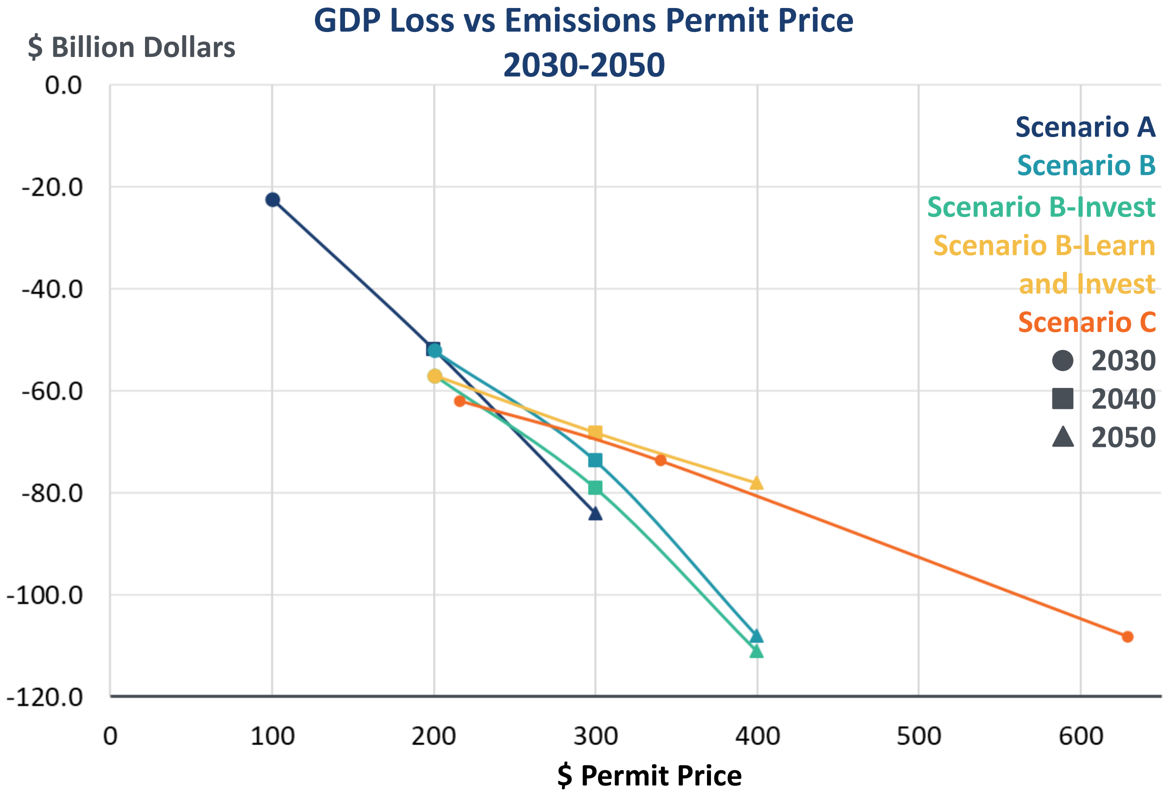


Summary – Emissions Levels and GDP by Permit Price

Scenario B-Learn and Invest achieves the most economical emissions abatement trajectory.

- The $200-300-400/ton carbon price progression reduces emissions from ~90 MMT in 2030 to ~35 MMT in 2050.
  - CO_2 revenue investment in clean technology incentivizes ~20 MMT of emissions abatement in 2050;
  - Cost efficiencies through learning in clean technology adoption further reduces emissions by ~10 MMT in 2050
- Despite the rapid rate of emissions abatement by 2050, GDP losses of $80 billion in 2050 (-2.6%) are lowest of all scenarios.

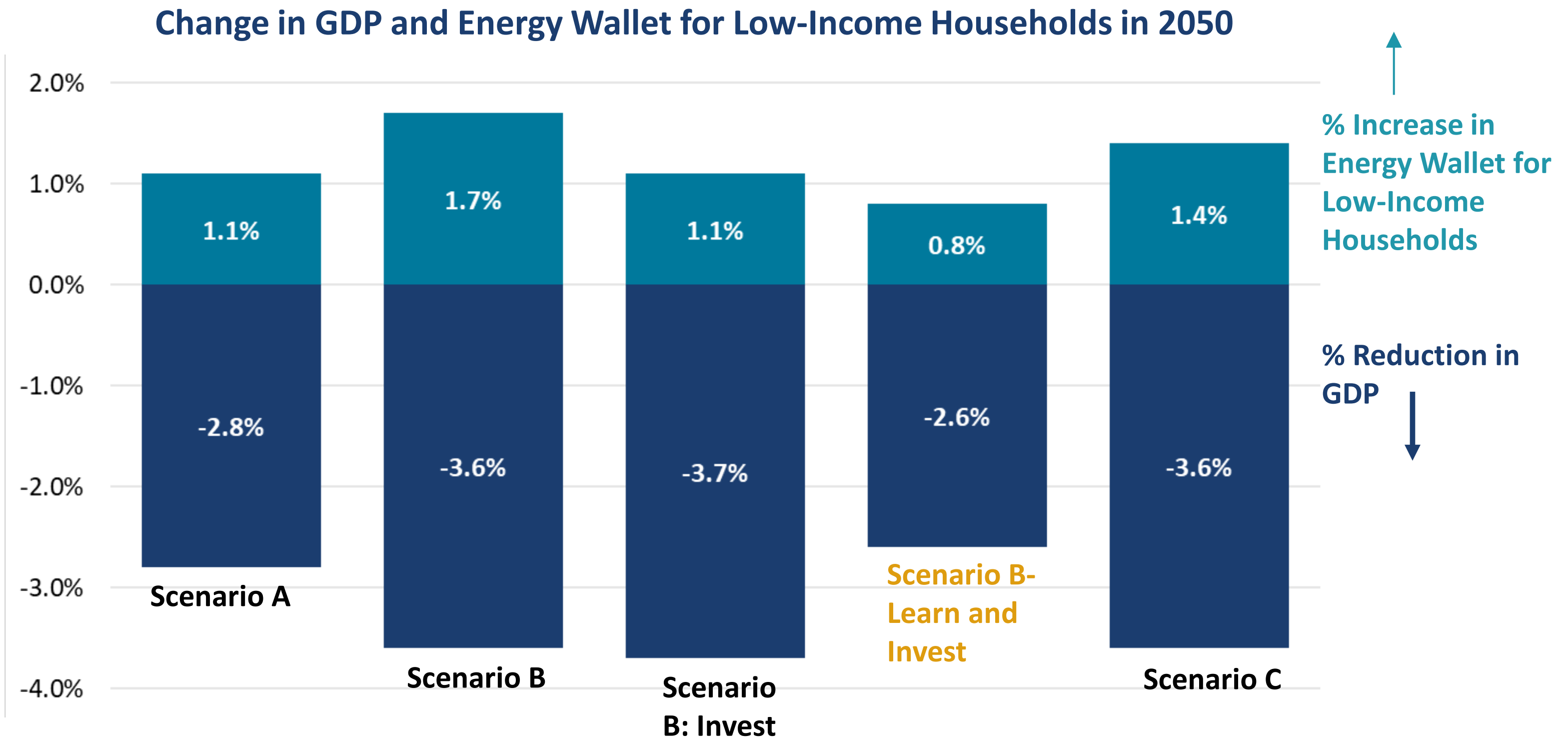




Impact on Lower Income Households

The economic efficiency of Scenario B-Learn and Invest extends to households' energy wallet – the total amount a household spends directly on energy as a portion of gross income (typically ranging from 6-10%).

- Revenue investment in clean technology increases economic activity in the industrial sectors that support electrification, resulting in more job opportunities (relative to other scenarios) for households.
- Learning in clean technology adoption reduces abatement costs for production sectors, resulting in more spending in employment, which in turn increases household income and less GDP reduction.



In other studies, we have adjusted exemptions and revenue recycling to show that critical sectors can be held completely cost-neutral, if politically desired.

Scale and Use of Carbon Tax Revenues

Revenues from carbon pricing can go directly back into climate investments, accelerating the transition into a more fossil-free economy.

- The table below shows the potential impact of using a hypothetical 2024 carbon tax revenues in six states, at $50/mt CO_2 applied to all sources of emissions, to fund residential air-source heat pump (ASHP) adoption
  - This carbon tax would raise 3–8% of those state governments' annual expenditures
  - ASHPs are assumed to have an average installation cost of $30,000 per household
  - Except in MA, these annual carbon pricing revenues would be more than enough to cover full costs of converting 5% of households having fossil heating.

Potential Impact of Reinvesting Carbon Pricing Revenues into ASHPs (2024)

State	2024 emissions (mmt CO2)	$50/mt CO2 tax revenues (millions)	CO2 Tax Revenue as % of State Expenditures	Number of Households with Fossil Fuel Heating (millions)	Tax Revenues needed to install ASHPs at 5% of households with FF
Illinois	164.0	$8,199	7%	4.07	75%
Massachusetts	58.1	$2,904	3%	2.20	114%
New Jersey	87.8	$4,392	5%	2.90	99%
Maryland	48.8	$2,438	4%	1.28	79%
Colorado	79.6	$3,979	8%	1.80	68%
Washington	73.8	$3,690	5%	1.23	50%

Source: EIA, U.S. Census Bureau, Brattle Analysis.

- In addition to the emissions reductions from ASHP installations, a $50/mt CO_2 price raises the cost of natural gas by ~$2.65/Dth, which is ~66% of an assumed commodity cost of $4/Dth and ~20-25% of the all-in variable charge on a typical residential gas bill.
  - This would likely reduce consumption by 5-10%, roughly matching the emission reductions from the ASHPs.

Interpretation and Implications

The foregoing is not offered as a detailed or highly calibrated model of possible policies in NY, nor of recommended values for carbon pricing. Instead, it is indicative of what climate policy questions can be addressed with linked CGE and power system modeling, and what general patterns of results and sensitivities are likely to be found. These include:

$200 – $400/mt

CO_2 prices in this range are needed to motivate (and subsidize) large end-use substitutions in hard-to-abate sectors (such as older urban housing, or heavy-duty transportation; see appendix for cost evidence)

But high carbon prices need not induce material economic losses or sectoral hardships. The revenue can and should be recycled

Revenue Recycling

Targeted reinvesting can protect vulnerable customers and critical economic sectors or promote greater clean tech adoption

Directing 70% of revenues to transport and building technologies produces more abatement at similar GDP cost than returning all revenue as household dividends.

Learning

If the available solutions only include technology with existing costs and performance, costs are high or less is accomplished.

Targeting revenues back to sectors where there are economies of scale or potential large gains in efficiency could cause more emissions reductions for less carbon taxation.

Power Feedbacks

Deep electrification materially increases electricity demand and has power system consequences that CGE or I/O modeling cannot capture (such as dramatic shifting to winter peaking)

Accordingly grid expansion costs and reliability constraints must be modeled alongside the broader economy.

Many other policy alternatives can be evaluated with this type of modeling, including strict mandates on sectoral fuel usage, regional border "leakage" restrictions, the presence or absence of carbon policies in adjacent regions, or pooled collaboration with carbon markets elsewhere.

Appendix

Background on NY Demographics and Economy (2023)

- **Population –** 19.9 million, of which:
  - 8.5 million in NYC
  - 7.7 million total households with ~32% (~2.5 million) deemed low income (at or below 60% of state median income)

- **State GDP** – about $2.3 Trillion ($115,000 per capita);
  - State operating budget about $130 Billion of which $80–90 B from personal and business taxes.

- **Commercial Sectors Profile**
  - Services: $921 B (42.2%)
  - Finance and Insurance: $433 B (19.8%)
  - Government: $210 B (9.7%)
  - Trade: $194 B (8.9%)
  - Information: $183 B (8.4%)
  - Energy-Intensive Manufacturing: $76 B (3.5%)
  - Construction: $65 B (3%)
  - Transportation: $49 B (2.2%)
  - Utilities: $29 B (1.3%)
  - Other Manufacturing: $16 B (0.8%)
  - Agriculture: $4 B (0.3%)

- **Population Demographics by Income Level***;
  - Under $25k (16.7%) — $25k–50k (15.6%) — 50k–75k (14.1%) — 75k–200k (37.7%) — over $200k (15.9%)

**Household income levels from the US Census Bureau.*

Background on NY Demographics and Economy (2023)

- **Total energy use and mix**: 3,437 trillion BTU in 2023 at $74.1 billion expense
  - $3,756 per capita vs $85,733 per capita income (so energy = 4.4%)
  - Fuel use = 1,342 Tr Btu gasoline and petroleum products, 1,347 natural gas, 288 nuclear, 273 renewables, 182 out-of-state sources
  - Energy consumption shares = 981 Tr Btu residential, 968 Tr commercial, 325 Tr industrial, and 1,163 transportation
  - 475.7 trillion BTU electricity
- **Electric sector**: 41,386 MW generating 11,918 GWh annually
  - Of which energy shares: 22% nuclear, 17% hydro, 6% solar and wind, 38% natural gas, .7% petroleum, 16% imports
  - Power system required to be 70% renewables by 2030, 100% clean by 2040
- **Carbon Dioxide emissions**: 165.5 million metric tons/year
  - 26.6 million TPY from electricity generation = 16% of state total
  - Transportation is dominant source of CO_2 at about 46.9%, followed by buildings' use of fossil fuels at 19.2%
- **Vehicles:** 9.3 million LDVs of which 3.5% are EVs

Perspective on Marginal Costs of Carbon Abatement

Whether a given region will have high or low costs of abatement depends in significant part on the mix of industries and electric power system configuration it starts from, along with the age, type, and condition of buildings.

Equipment and retrofitting of home conversions to ASHP have been found to vary from a few $1000/unit* to $75,000 or more**

- A typical home with natural gas appliances avoids 5–10 tons of CO2 emissions/year from converting to electricity (if served by an entirely clean grid), or up to 200 tons in 20 years. If spending $50k net for conversions, this results in $250/ton avoided CO_2 cost.
- A recent Colorado pathways study by RMI et al. found deep housing retrofits cost $216/ton***

The decarbonization supply curve can be fairly low and flat up to a moderate level of abatement, then tends to become quite steep (for both end-use electrification and power systems).

Cost range ($/mt)	Examples
Negative/ self-funding -$100s to $10s/ton	New housing, rooftop solar in sunny regions, hybrid and low cost EVs
Low Zero to $40s/ton	Gas wellhead emissions controls, industrial and power fuel-switching, “drop-in” appliance replacements, landfill gas capture
Medium $50 to $150	Energy efficiency improvements, ASHP where ducting and power capacity in place, some industrial CCS
High/ difficult to abate $150 to $500 or more	Heavy duty transit EVs, aviation, deep building retrofits, restaurant conversions, manufactured RNG, H_2

* Boston is piloting a new type of heat pump that’s as easy to install as a window AC | WBUR News, Feb 10, 2026
** ComEd Converts 450 Homes to All-Electric Through Whole Home Electric Program | ComEd – An Exelon Company, Sept 30, 2024
*** Colorado's Clean Affordable Climate Pathways Technical Report, p. 116, Dec. 2025

Findings in Other CGE Carbon Pricing Models

CGE models have been widely used in carbon pricing models. Price levels found in our preliminary analysis are not uncommon.

- "*Using Carbon Tax to Reach the U.S.'s 2050 NDCs Goals—A CGE Model of Firms, Government, and Households*" (Yan, Gupta, Maheshwari, 2023).
  - Uses a two layer-CGE Cobb-Douglas model to evaluate economy-wide carbon tax pathways in the U.S.
  - Analysis for the United States over 2020–2050, with the carbon tax varied to meet progressively tighter emissions targets
  - The modeled carbon tax rises from \$42/tCO2 in 2020 to \$149/tCO2 in 2030 and about \$1,006/tCO2 in 2050 for an 83% emissions reduction below 2005 levels

- "*US economy-wide decarbonization: Sectoral and distributional impacts* (Becker et al., 2025).
  - Uses a CGE model linked to a detailed electricity-sector model
  - Analysis for the United States through 2050, varying technology availability under a net-zero constraint
  - The modeled carbon price reaches nearly \$800/tCO2 in 2050 in the base case, and falls to roughly \$500/tCO2 under more favorable technology assumptions

- "*Boosting Sluggish Climate Policy: Endogenous Substitution, Learning, and Energy Efficiency Improvements*" (Bretschger, Leuthard, Miftakhova, 2025).
  - Uses the CITE model, a dynamic CGE model with endogenous growth and learning
  - Analysis for Switzerland, modeling a pathway to net zero by 2050
  - The carbon price needed to hit net zero by 2050 falls from 401 CHF to 232 CHF (~\$290/tCO2) when endogenous technology effects are included

BEYOND Model

BEYOND is Brattle's proprietary recursive dynamic Computable General Equilibrium (CGE) model.

- **Aggregate regions and sectors cover:**
  - 50 states + Washington, DC
  - 71 sectors based on BEA national summary files
  - 5 household income levels
- **Simulates Key interactions in US economy:**
  - Interactions between industries, households, and government
  - Model dynamics based on circular flow of economic activity
- **Key model outputs:**
  - CO_2 Emissions from fossil fuel combustion
  - GDP impacts
  - Price effects (wages, return on capital, prices of goods and services)
  - Economic output by sector and region
  - Consumption of goods and factors of production by sector and region

BEYOND

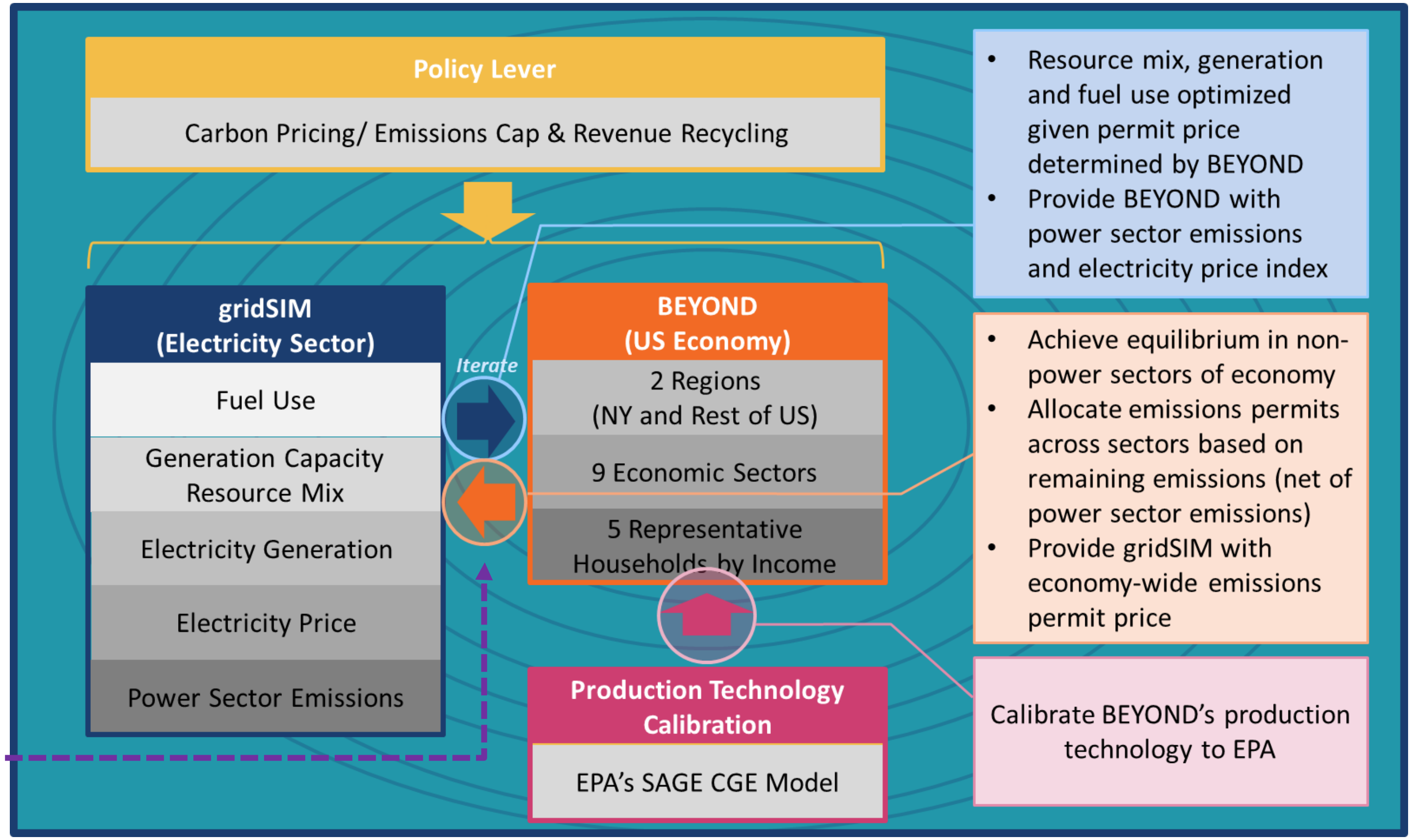
BEYOND-gridSIM Iteration

Decarbonizing the economy is likely to lean heavily on clean electricity, so it is necessary to couple BEYOND's macroeconomics to gridSIM's power system detail to achieve internally consistent views of carbon pricing, electricity generation, energy consumption, and macroeconomic growth.

BEYOND used to assess the economy-wide impacts of carbon prices or a hard cap.

gridSIM used to refine BEYOND's electricity sector estimates for quantities and costs of required electricity generation.

Models are iterated to achieve reasonable convergence on costs and electricity needs.



Reference Scenario Calibration

Model has been calibrated to external data points on emissions, economic outlook and permit price:

- **Emissions factors (EFs)** for fossil fuels adjusting for the inclusion/exclusion of upstream emissions
  - Energy Sector Greenhouse Gas Emissions under the New York State Climate Act, 1990-2021," Table D-2, pg. 101
- **GDP growth and macroeconomic indicators**
  - GDP projections based on Annual Energy Outlook 2023 (AEO 2023).
- **Sector-specific emissions in New York**
  - 2024 New York State Greenhouse Gas Emissions Report (NY State, Department of Environmental Conservation)
  - NYCI *Preliminary Analysis* Data Annex (NY State, NYSERDA, Department of Environmental Conservation)
  - Integration Analysis Annex 2: Key Drivers and Outputs, 2023 Revised (E3)
- **Load and capacity**
  - New York Load and Capacity Data: "Gold Book" (NY ISO)
- **Government models**
  - EPA SAGE CGE Model (EPA)

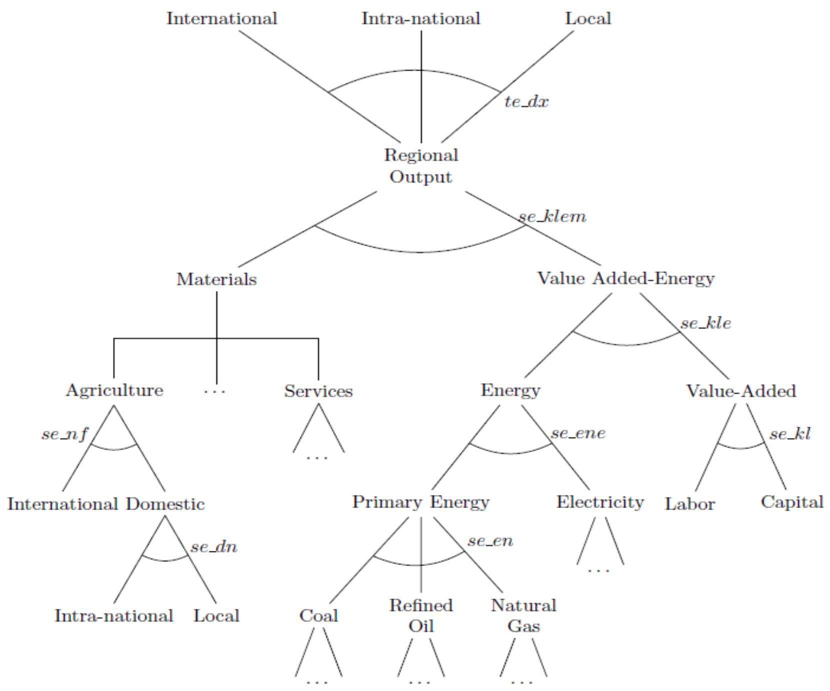
Electrification Technology Calibration

For each sector of the economy, BEYOND calibrates fossil fuel consumption and the technological ease at which a sector can decarbonize (elasticities of substitution between fossil fuels and electricity; energy and value-added)

- BEYOND by default calibrates its production functions and trade activity to the US EPA's SAGE model,* a detailed general equilibrium model of the US economy.
- In each model year, we use the emissions permit price and sectoral emissions abatement response (specified in Preliminary Analysis) to calibrate NY's sector specific capacity for electrification.
- This captures the electrification technology at the sector level that's consistent with State/NYSERDA's view.

* SAGE Model Documentation, Version 2.1.1, U.S. Environmental Protection Agency
https://www.epa.gov/environmental-economics/sage-model-documentation-version-211

Constant Elasticity of Substitution (CES) Production Function Used for Manufacturing Sector in SAGE Model



Power Sector Expansion Modeling: gridSIM

gridSIM has been used in many market design and utility resource planning studies, especially for decarbonization planning. The model optimizes hourly market operations and the expansion of generating capacity and new transmission.

INPUTS

Supply
- Existing resources
- Fuel prices
- Investment/fixed costs
- Variable costs

Demand
- Representative day hourly demand
- Capacity needs

Transmission
- Zonal limits
- Intertie limits

Regulations, Policies, Market Design
- Capacity market
- Carbon pricing
- State energy policies and procurement mandates

gridSIM OPTIMIZATION ENGINE

Objective Function
- Minimize NPV of Investment & Operational Costs

Constraints
- Planning Reserve Margin
- Hourly Energy Balance
- Operational Reserve Requirement
- Regulatory & Policy Constraints
- Resource Operational Constraints
- Transmission Constraints

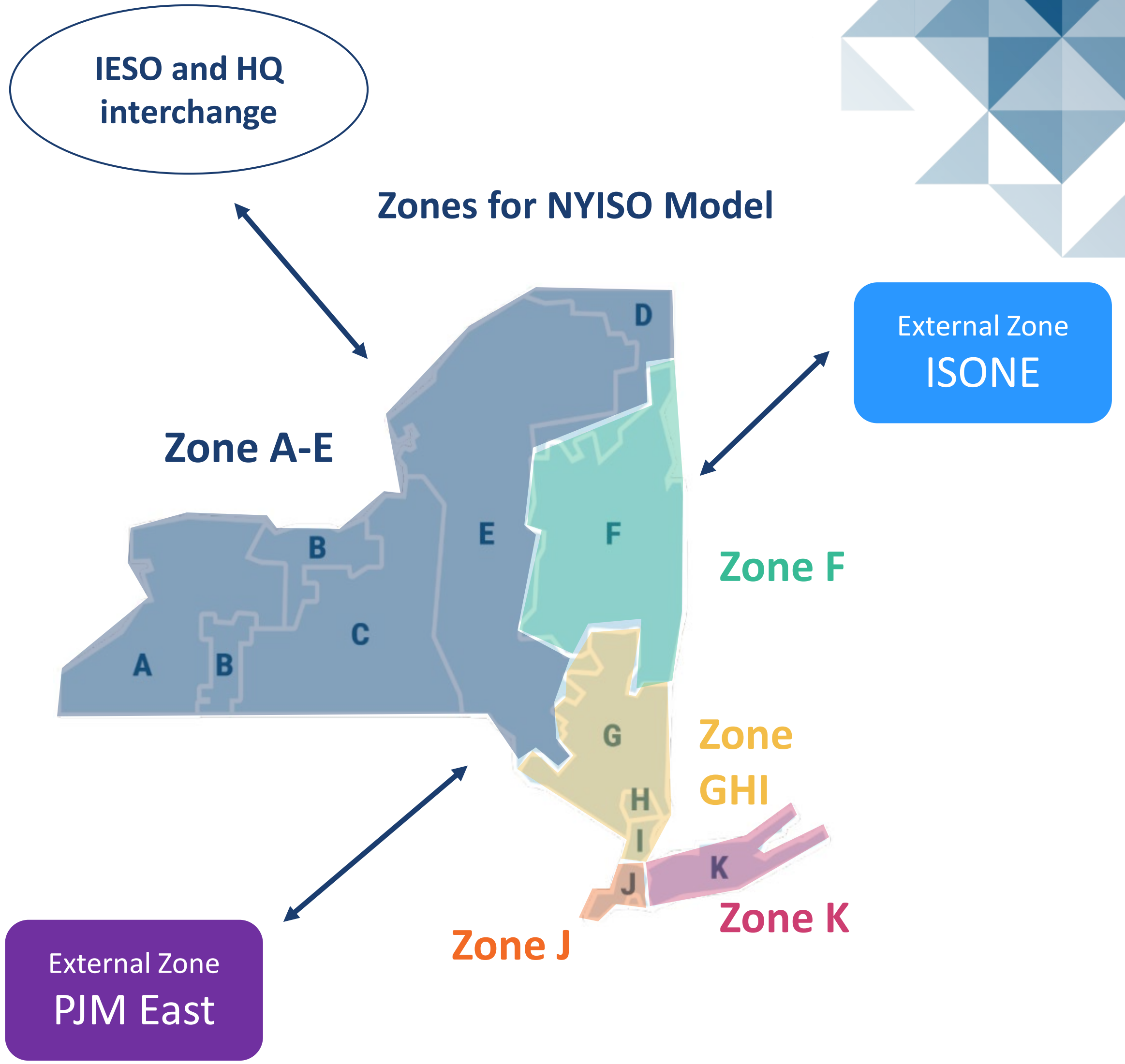
OUTPUTS

- **Annual Investments and Retirements**
- **Hourly Operations**
- **Marginal Costs of Capacity, Energy, and Reserves**
- **System and Customer Costs**
- **Emissions and Clean Energy Additions**
- **Supplier Revenues**

gridSIM Model Topology

gridSIM uses a pipe-and-bubble representation of the NYISO footprint, aggregating generators and loads into a multi-zonal energy model.

- **Five zones** are modeled in NYISO, aggregated up from NYISO's 11 load zones: Zones A-E, Zone F, Zone GHI, Zone J, and Zone K.
- **Two external zones** are modeled: ISONE and PJM East, and interchange with IESO and Hydro-Quebec is represented based on historical flow data.
- Inter-zonal **transmission flow limits** from NREL ReEDS between each zone that define forward and reverse flow limits.
- **Existing generator data** from NYISO Gold Book 2024, aggregated into the 5 zones shown at right.
    - Includes planned generation additions and retirements (e.g., through 2028/2030) as model input (from Velocity Suite's Generating Unit Capacity dataset).
    - Model-based economic decisions thereafter.
- **Renewable generation profiles** sourced from renewables.ninja vary by region to reflect wind and solar resource diversity.



Base map source: NYISO.

Overview of Modeled Reference Scenario Policies

Power Sector

- **The Climate Leadership and Community Protection Act (CLCPA) includes:**
  - A requirement for the electricity grid to be emissions-free beginning in 2040
  - A goal to reach 70% renewable electricity by 2030[1]
    - Our model assumes a linear glide path from the current renewable penetration rate (30%)[2] to 70% by 2030
  - Procurement targets for OSW and storage[3]
    - 6,000 MW of energy storage by 2030
    - 9,000 MW of offshore wind by 2035[4]

Commercial, Industrial and Residential Sectors

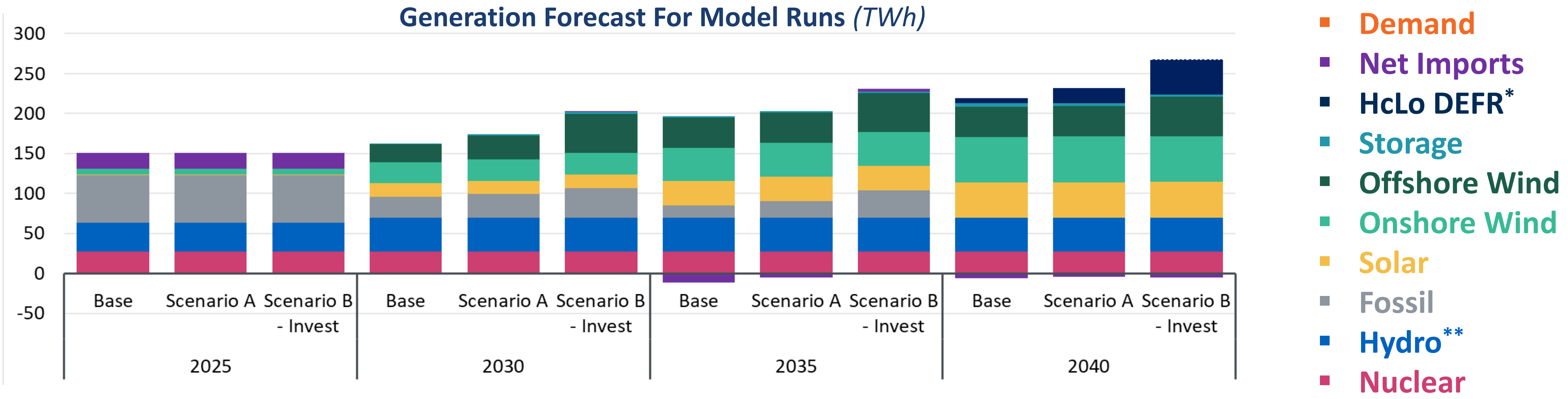
- **We assume 50% of the abatement achieved under Integration Analysis Annex 2, Reference Case 2023, which includes the following policies:**
  - Corporate Average Fuel Economy (CAFE) Standards
  - Advanced Clean Cars II and Advanced Clean Trucks Zero-emission vehicle mandates
    - 100% ZEV light-duty sales by 2035, 100% ZEV medium and heavy-duty sales by 2045
  - Updated building code standards (15% heat pump sales by 2030)

Notes:
[1] State Draft Energy Plan utilizes a 2033 date for this milestone in its Pathway Analysis.
[2] In 2024, around 130 TWh total was generated in NY; renewable generation was around 37 TWh (NYISO 2025 Gold Book).
[3] New York also has a Behind-The-Meter (BTM) PV installation goal. This is not explicitly modeled, since gridSIM represents net load (net of BTM generation), but is captured implicitly by the difference between gross and net load.
[4] The power sector modeling was conducted prior to the cancellation of the Public Policy Transmission Need identified to construct transmission for New York City OSW generation, which may make achieving this target more challenging.

gridSIM Generation Mix in NYISO

Generation forecasts across three scenarios show the increase in electricity demand driven by carbon prices:

- The base case aligns with the **NYISO 2024 Gold Book Baseline Forecast** reflecting load growth of around 2% each year from new large loads, electrification of heat and transport, etc.
- Generation in Scenario A shows around a 5% increase in 2040 load compared to the base case, whereas B-Invest shows a ~20% increase. Increased generation largely comes from wind and high-capital-low-operating cost dispatchable emissions free resources.
- Fossil generation gradually phases out by 2040 due to CLCPA and is offset by increasing solar and onshore/offshore wind generation.



Notes:
*DEFRs are Dispatchable Emissions Free Resources, an unspecified technology as characterized by the NYISO in its modeling. DEFRs do not exist as a single specific commercially viable option today and may be in various stages of research and development. Typically, high capital and low operating cost (HcLo) units are technologies like nuclear, and low capital high operating cost (LcHo) units are thermal units with clean fuel.
**HQ imports are grouped into "Hydro." "Net Imports" reflect all other zone connections. Champlain Hudson Power Express (CHPE) transmission line COD modelled as beginning in 2026.