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The role of electrification induced peak loads and gas infrastructure constraints on decarbonization pathways in New York State

Yuezi Wu [a,*], Michael Waite [a,b], Terence Conlon [a], Vijay Modi [a]

[a] Department of Mechanical Engineering, Columbia University, 220 S.W. Mudd Building, 500 West 120th Street, New York, NY, 10027, USA
[b] The American Council for an Energy-Efficient Economy, Washington, DC, USA

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ABSTRACT

New York State policies impose time bound targets for both progressively larger emissions reductions and increasing fractions of zero-carbon electricity. This paper compares pathways to meet desired emissions reduction goals with or without specified zero-carbon electricity targets. We show that when an additional lever for reducing emissions – electrification of buildings and transportation – is considered, New York State can meet the same desired emissions targets at considerably lower levelized costs of electricity (LCOEs) if specified zero-carbon electricity targets are relaxed. We also investigate how electrification induced new peak loads and limits on new gas infrastructure impact state decarbonization pathways. To meet the 40% emissions reduction target by 2030, two new illustrative approaches are considered. One pathway with 100% electrification of buildings and vehicles, 11 GW of wind and utility-scale solar capacity and 21 GW of new gas generation capacity leads to an LCOE of $63/MWh. An alternate pathway that precludes new gas generation capacity requires 60% electrification, nearly doubles the installed wind and solar capacity, and results in an LCOE of $72/MWh. Due to the added emissions reduction benefits from electrification, both illustrative pathways are lower cost than a pathway in which the same 40% reduction target is combined with a specified 70% renewable target - at an LCOE of $92/MWh. We also show that LCOEs can be kept manageable through shaving of new higher peak loads that arise from electrified heating. Moreover, the LCOE impact of limiting peak natural gas flow to its current quantities is found to be small.

1. Introduction

Nearly all decarbonization studies have recognized the importance of reducing fossil-fuel based electricity generation and electrifying buildings and vehicles as the broad arcs of dramatically reducing energy-related greenhouse gas (GHG) emissions [1–3]. In the absence of comprehensive federal policy, projected decarbonization pathways in the U.S. are shaped by state and city-specific policies [4] that define time-bound GHG emissions [5] and electricity grid [6] mandates; sector-specific targets for electric vehicles [7] and building end use electrification [8]; and fossil fuel infrastructure restrictions [9].

To date, state policies have prioritized deep penetration of zero-carbon resources in the electricity grid [10], driving towards complete elimination of fossil fuels in the electricity supply in the next two decades [11]. Outfitting fossil fuel generators with carbon capture technology requires a significant investment in capture, utilize, and store technologies [12]. Shifting current fossil fuel-based transportation and building-sector end-uses to electric technologies would allow one to utilize zero-carbon electricity supply to drive down emissions in those two sectors [13]. However, because the marginal cost of emissions reductions increases with deeper penetration of renewables [14], prioritizing a cleaner electric grid can lead to high electricity supply costs. Previous research has found fossil fuels play an important role in meeting peak electricity loads and net loads during periods of limited solar and wind supply [15]. However, existing and new gas turbines' prospects are unclear because the plants' approval, lifespan, and capacity utilization are unknown given the need to dramatically reduce GHG emissions [16]. On the other hand, compared to electricity's 31% share of total US energy-related CO_2 emissions in 2019 [17], fossil fuels burned in buildings and vehicles contribute 49% of the country's emissions and have larger decarbonization potential.

A recent analysis of the decarbonization pathways in New York State (NYS) by the authors of this paper found that prioritizing heating and vehicle electrification allowed the state to meet GHG emissions targets specified in the Climate Leadership and Community Protection Act (CLCPA) [18] while keeping per-unit costs of electricity low [19]. In these

* Corresponding author.
E-mail addresses: yw3054@columbia.edu (Y. Wu), mwaite@aceee.org (M. Waite), tmc2180@columbia.edu (T. Conlon), modi@columbia.edu (V. Modi).

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decarbonization scenarios, electrified demand facilitated system affordability by (1) reducing curtailment of installed wind and solar; (2) limiting emissions without requiring the replacement of all gas infrastructure; and (3) dividing existing fixed costs over larger demand quantities. While these conclusions are similar to others in the literature – such as [20,21] – they also produce another set of issues that have not yet been fully addressed, and are reflective of gaps in the wider literature.

First, Ref. [19] did not include costs for distribution system upgrades in its cost-minimizing energy system model, which reflects common practice in existing research employing capacity expansion models [22, 23]; although some advanced models have incorporated such costs in objective functions [1,24], they do not include different costs for high- and low-density areas. Accordingly, the grid costs of electrification – costs that are likely to be socialized among all rate-payers in a utility area – were likely underestimated [25]. Second, capacity expansion models tend to include fossil fuel generation technologies, but few models in the literature integrate policies that may restrict new deployment. In this vein, Ref. [19] found that to meet the state's dispatchable generation needs and larger demand peaks, low-cost gas generation capacity was expanded instead of more-expensive battery storage, despite limited public appetite for new gas-based infrastructure in places with aggressive climate policies [26]. Third, electrification rates were assumed to be uniform throughout the state in Ref. [19], despite the fact that NYS contains multiple climate zones and transportation paradigms with disparate zonal cost assumptions that may yield a more spatially heterogeneous adoption of heating and vehicle electrification [27]. The novel fossil fuel heating load and electrification model [28] incorporated into the model introduced in Ref. [19] allows these effects to be captured. Lastly, in Ref. [19], no methods of managing large electrification-induced electricity demand peaks were considered beyond buildout of new dispatchable electricity generation, despite the likelihood of efficiency improvements and flexibility strategies being implemented to manage the demand load [29,30].

The current paper aims to fill these gaps, building on the earlier work and addressing open questions in the current literature. First, the costs of distribution upgrades due to electrification are adopted, per recent spatially explicit estimates provided to the NYS Climate Action Council [31]. Second, in some scenarios, peak shaving is applied to electrified space heating, which would otherwise induce high electricity peaks during cold weather. There is broad agreement that electrification of heating should be preceded by envelope efficiency upgrades [30,32]. There are however significant costs associated with implementing such upgrades, particularly at the scale that would be needed to minimize electricity peak demand increases. We consider a less restrictive approach where peak shaving is accomplished through maintaining limited use of fossil fuel in existing building space heating systems during the transition to electric heat pumps (EHPs). Here, recent work has shown that this dual source heating method can mitigate the need for new low-capacity factor generation and distribution infrastructure [28]. Moreover, constraints that prohibit new gas generation capacity or increases in peak gas consumption are simulated. Lastly, the value of heterogeneous electrification rates is explored. Altogether, this paper addresses the limitations of previous decarbonization modeling work in NYS, fills gaps in the current literature, and provides a better understanding of the potential pathways for a regional energy system undergoing a low-carbon energy system transition.

2. Methodology

This paper applies the open-source System Electrification and Capacity TRansition (SECTR) model formulated for the NYS energy system (SECTR-NY) [19] to a series of pathways meeting zero-carbon electricity percentage (ZCP) goals and GHG emissions reduction targets (with respect to a 1990 baseline) [18]. For the current analysis, some additional considerations and changes are made compared to the original model in Ref. [19]. Section 2.1 introduces the key mathematical descriptions of the updated SECTR-NY; Section 2.2 shows the considerations on electrification induced peak loads and gas infrastructure constraints; Section 2.3 defines the decarbonization pathways and their parameters.

2.1. Introduction to SECTR-NY

SECTR-NY is a linear program with four nodes representing NYS subregions (Supplementary Fig. S1 presents the nodal map). For the following simulations, its objective function minimizes the statewide levelized cost of electricity (LCOE), as defined below by Eqs. (1) and (2). SECTR-NY quantifies GHG emissions for three dominant energy sectors (electricity, buildings, and on-road vehicles) based on spatially heterogeneous hourly electricity demands, generation technologies, and capital and operating costs; inter-nodal transmission limits; energy storage; temperature-dependent electric vehicle charging demands; and electrified building load time series. A full mathematical description of the SECTR-NY formulation is included in Supplementary Materials Section S1 of this paper.

$$objective\ function = minimize(LCOE) \tag{1}$$

$$LCOE = \frac{C_{newcap} + C_{generation} + C_{existingcap} + C_{distribution}}{\sum_{i \in I}\sum_{t \in T}\left(D^t_{elec,i} + D^t_{heat,i} + D^t_{veh,i} - X_{btmpv,i} * W^t_{btmpv,i}\right)} \tag{2}$$

The $LCOE$ in Eq. (2) consists of the total costs in the model period in the numerator divided by the total on-grid electricity demand in the denominator. The total costs include costs of: new generation, storage, and transmission capacity, C_{newcap}; electricity generator operations, $C_{generation}$; existing transmission and generator capacity, $C_{existingcap}$; distribution upgrades due to new electricity demand, $C_{distribution}$ (see Supplementary Material Section S1.2.2).

The on-grid electricity demand is the sum of existing demand, $D^t_{elec,i}$, electrified building demand, $D^t_{heat,i}$, electrified vehicle charging demand, $D^t_{veh,i}$, after subtracting the behind-the-meter solar generation that is computed by the capacity, $X_{btmpv,i}$, and the potential electricity generation, $W^t_{btmpv,i}$. Total demand is aggregated by nodes, i, and hours, t. The electrified building and vehicle demand are the products of the electrification rates (decision variables) and projected full building and vehicle electrification demand. As introduced in Ref. [28], electrified building loads include demand for space heating, domestic hot water, and other fossil fuel end-uses (primarily cooking).

The LCOEs in the original SECTR-NY [19] consider costs from generation and transmission, which are validated to be accurate compared to the current NYS electricity supply prices. In this paper, a modified LCOE that accounts for the capital expenditures of distribution upgrades – resulting from the new load peaks due to electrification – is minimized. This allows the model to capture the relationship between nodal electrification rate and differentiated nodal distribution upgrade costs. Electricity distribution system upgrade costs are estimated from a report presented to the New York State Climate Action Council [31]. Here, the cost of upgrade varies across nodes[1]: \$35/kW-year, \$61/kW-year, \$199/kW-year, and \$110/kW-year for Nodes 1 to 4, respectively. The highest costs of \$199/kW-year are for the node corresponding to New York City, as one would expect in a densely built space. Other grid maintenance and operation costs are excluded from the LCOE optimization. Note that we do not include any consumer side costs of electrification.

On grid supply side, the existing electricity system in NYS is carefully modeled in SECTR-NY, and the model allows for expanding new

[1] The geographical locations of upstate Node 1 and Node 2 (mainly the areas between Buffalo and Albany) and downstate Node 3 and Node 4 (mainly the New York City and Long Island), are shown on the map in Supplementary Fig. S1.

capacities of generation, battery storage, and transmission. As the metrics of the grid, the model introduces ZCPs and renewable electricity percentages as decision variables, which are constrained to be equal or greater than specified targets in some scenarios. Zero-carbon electricity includes wind, utility-scale solar, hydro, and nuclear generation, while renewable electricity excludes nuclear. The nodal energy balance, generation and storage technologies, transmission constraints, and ZCPs constraints are introduced in Supplementary Material Section S1.2.4, S1.2.6-S1.2.13.

In this study, carbon dioxide equivalent (CO_2e) emissions for fossil fuels [33] use 20-year GWPs and recent estimates of natural gas leakage [34], as codified in CLCPA [18]. SECTR-NY considers all energy-related GHG emissions. However, this paper narrows the scope to the three dominant sectors: (1) electricity generation, (2) residential and commercial buildings, and (3) on-road vehicles, which currently produce 86% of all energy-related emissions in NYS, per Supplementary Table S11. Energy-related emissions from other transportation, industrial uses, and waste incineration are excluded here. Thus, the GHG emissions reductions are calculated based on emissions of these three sectors in the simulated year compared to equivalent sector values in 1990.

2.2. Modeling electrification induced peak loads and gas infrastructure constraints

The gas infrastructure examined in this paper includes natural gas-based generation and peak natural gas consumption. In scenarios that do not allow new gas turbines, the total capacity of existing gas turbines and new gas turbines cannot exceed the current gas turbine capacity, while replacing existing gas turbines with new ones is allowed. In scenarios that limit peak gas consumption to current statewide and nodal peaks, the existing nodal and statewide peak natural gas peak demand is retrieved from the SECTR-NY current scenario [19]. This study does not model the natural gas system, but rather imposes constraints that reflect potential decisions about whether or not to expand said system.

In NYS, the current peak electricity demand due to the cooling load during summer is 34 GW. However, at 100% building and vehicle electrification, the peak load increases to 83 GW, mainly resulting from the high electric heating load during extremely cold weather. The new peaks will reduce the grid load factors, thereby requiring larger dispatchable generation capacities and reducing the utilization of generators or batteries.

To simulate a future system in which heating electrification-induced increases in electricity demand peaks are limited, a method of shaving peak electric loads is explored. This peak shaving is achieved by leveraging a dual-source heating system that maintains existing fossil fuel-based heating capabilities to limit the use of EHPs at the coldest ambient temperatures. In practice, the implemented approach to peak shaving restricts EHPs to provide no more than 50% of the nodal peak aggregate thermal demand with fossil fuel-based devices meeting the remaining load. With 100% electrification, this peak shaving method reduces the building electrified load by 6.6%, and keeps 4.6% of the existing fossil fuel consumption in the building sector.

To illustrate the load effects of peak shaving, Fig. 1(a) shows the statewide peak electricity load and electricity load factor versus electrification rate. Peak electricity demand at 100% electrification is substantially lower with peak shaving (59 GW) than without (83 GW), yet both represent a significant increase over the current peak electricity demand. The system load factor initially increases with electrification before the additional EHP load causes the heating-driven winter demand peak to exceed the current cooling-driven summer demand peak at approximately 25% electrification. Peak shaving significantly increases the load factor for all electrification rates above 25%: Even at 100% electrification, peak shaving yields a load factor of 0.54, substantially higher than the 0.39 value for demand without peak shaving. The current value of load factor is 0.55. Details on nodal electricity demand with or without peak shaving are shown in Supplementary Material Table S1 and Fig. S2.

2.3. Decarbonization pathways

This paper defines two sets of decarbonization pathways representative of policy targets and broad energy planning considerations. In both sets, the GHG emissions reduction targets are consistent across all scenarios and with the CLCPA. Pathways are not continuous incremental computations in time, but are discrete representative scenarios along an imagined path constructed using reasonable author-imposed intermediate emission reductions in 2025, 2035, 2040, and 2045, per Fig. 1(b). The two sets of pathways considered are:

1. Pathways with specified ZCP targets. These generally need higher renewable capacities and are called “HighRE” pathways in this paper.
2. Pathways without specified ZCP targets. In these pathways ZCP is a decision variable. These pathways generally need lower renewable capacities and also lead to lower LCOE values. They are called “LowLCOE” pathways in this paper.

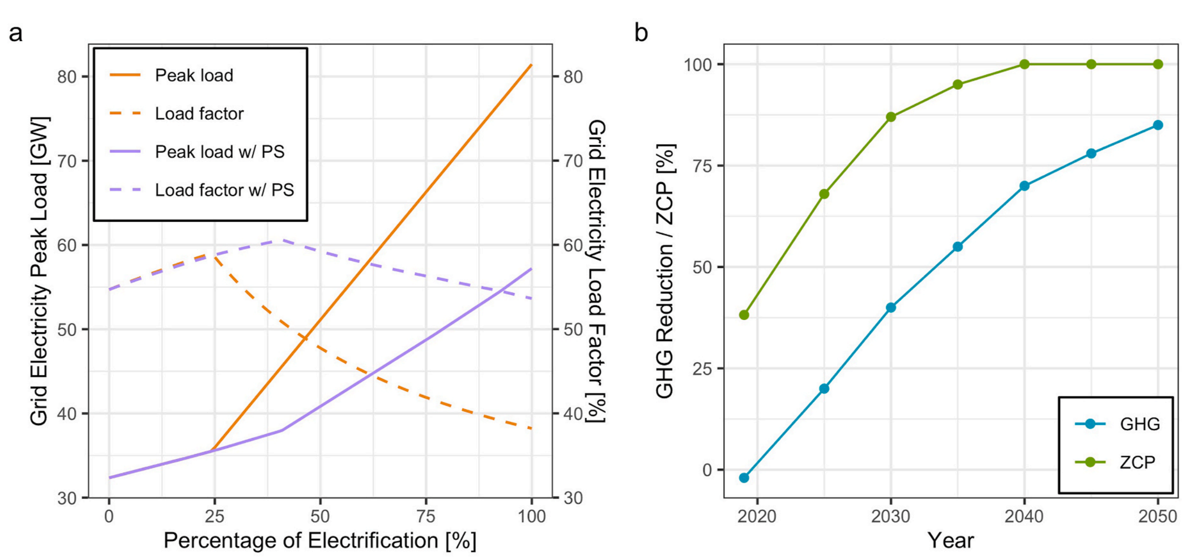

Fig. 1. | (a) Statewide electricity load peak (left y-axis) and load factor (right y-axis) with and without peak shaving (PS); (b) GHG emissions reductions and zero-carbon electricity percentage (ZCP) for the simulated decarbonization pathways.

In both sets of pathways, LCOE is minimized for a specified GHG emissions reduction target. For all pathways, nodal electrification rates are decision variables. The default configuration constrains electrification rates to be equal for buildings and vehicles across all four nodes; scenarios are then evaluated with this constraint removed (i.e., allowing different electrification rates for buildings and vehicles and for different nodes). Building electrification includes space heating, domestic hot water, and other fossil fuel end-uses (primarily cooking), while vehicle electrification includes all on-road vehicles running on gasoline and diesel.

As shown in Table 1, pathway configurations are assessed across three vectors: 1) new gas turbine (GT) availability, 2) the presence of peak shaving, and 3) limitations on peak natural gas consumption at each node and statewide.

The flowchart in Fig. 2 presents the main steps to model the decarbonization pathways. In short, after setting up the SECTR-NY configurations and determining the pathway parameters, the model would run from 2025 to 2050 with 5-year intervals in a loop.

3. Results

HighRE and LowLCOE pathways representing all combinations of system configurations outlined in Table 1 are computed. In the following paragraphs, Section 3.1 presents results for the five selected decarbonization pathways through 2050; Section 3.2 more closely investigates optimal system characteristics in 2030; and Section 3.3 explores the effects of heterogeneous electrification rates.

3.1. Evaluation of decarbonization pathways through 2050

The results first show that the entire group of HighRE pathways is dominated by the ZCP requirements and demonstrate a highly similar solution space (see Supplementary Fig. S3). Therefore, the HighRE path with peak shaving, 20-year GT capital annualization, no natural gas peak demand limit – **HighRE_PS** – is selected as the representative pathway for the HighRE group. Supplementary Fig. S4 shows that natural gas peak demand limits have relatively little impact on the model-computed LCOE of the LowLCOE pathways group. Therefore, four easily

Table 1
Decarbonization pathway parameters.

Objective function	Minimize the levelized cost of electricity (LCOE) in dollars per MWh
GHG emissions reduction targets	Per NYS climate law (CLCPA): 40% reduction by 2030; 85% reduction by 2050. Author-defined 70% reduction by 2040 and intermediate targets for 2025, 2035 and 2045.
Zero-carbon electricity	For **HighRE** pathways - per CLCPA: 70% renewable generation by 2030[a]; 100% zero-carbon generation by 2040. Author-defined intermediate targets for 2025, 2035, 2045, and 2050. For **LowLCOE** pathways - Decision variable. (Pathways are not constrained to meet CLCPA targets.)
Electrification rates	Decision variables. The default case sets building and vehicle electrification rates equal across all four nodes.
New Gas Turbine (GT) options	1.20-year GT capital cost annualization (GT20)[b] 2. No new GT allowed (NoNewGT)
Peak shaving (PS)	With peak shaving (shown as "_PS") or without PS
Natural gas peak demand	Allow or do not allow peak nodal and statewide natural gas demands to exceed the model-computed current peaks.

[a] The model-computed ZCP is 87% with 70% renewable electricity in 2030.
[b] An option with 8-year new GT capital cost annualizations is discussed in the Supplementary Materials.

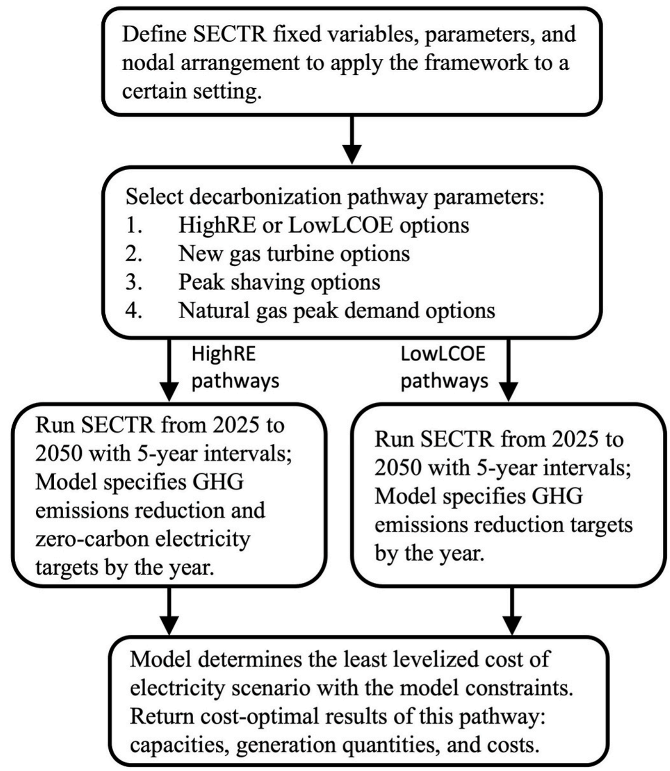

Fig. 2. | Flowchart for SECTR model solving the decarbonization pathway.

distinguishable LowLCOE configurations are selected for full pathway analysis: **GT20, GT20_PS, NoNewGT, NoNewGT_PS**. The starting point of all pathways is the "current scenario" from Ref. [19], which is simulated and validated in SECTR-NY as the existing energy system in2019.[2] Table 2 shows the key parameters of five illustrative pathways.

It's worth emphasizing that the distribution upgrade costs are included in the LCOE objective function, but they are subsequently removed from the LCOE results presented, as LCOE typically constitutes the "supply" portion of a utility customer's bill and these supply LCOEs can be compared with the numbers in the real-world and other models. Fig. 3 shows LCOE evolution and GHG emissions reductions along the decarbonization pathways, which vary in terms of ZCP and electrification rates. The HighRE_PS pathway contains significantly higher LCOEs

Table 2
Choices associated with five illustrative pathways (Y as yes, N as no).

	HighRE_PS	GT20	GT20_PS	NoNewGT	NoNewGT_PS
GHG emissions reduction targets	Y	Y	Y	Y	Y
Zero-carbon electricity targets	Y	N	N	N	N
Electrification targets	N	N	N	N	N
New gas turbine (GT) allowed	Y	Y	Y	N	N
Peak shaving applied	Y	N	Y	N	Y
Peak natural gas demand limited	N	N	N	N	N

[2] The nuclear generator in Node 3, fully shut down in 2021, is excluded in the SECTR-NY existing energy system configuration.

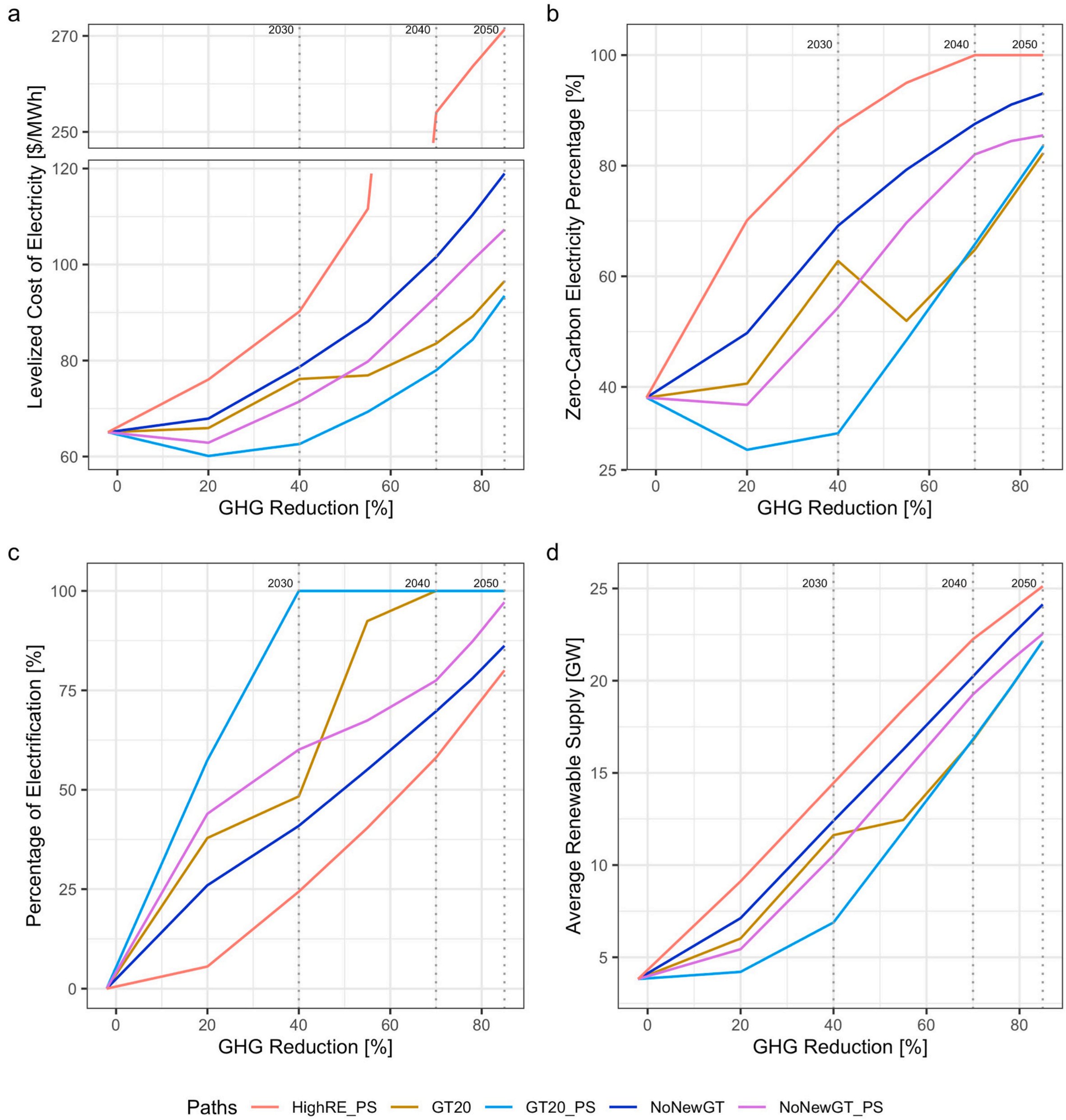

Fig. 3. | NYS decarbonization pathways showing (a) levelized cost of electricity, (b) zero-carbon electricity percentage, (c) building and vehicle electrification rate, and (d) total average renewable electricity supply (including behind-the-meter solar photovoltaic projected in the model). "GT20" indicates 20-year GT capital cost annualization; "PS" indicates scenarios with peak shaving.

(Fig. 3(a)) than the LowLCOE pathways, due to the ZCP requirements (Fig. 3(b)), and the emissions reduction benefits of electrification even at current grid emissions rates. Thus, the dominant decarbonization tradeoff is between ZCP (Fig. 3(b)) and electrification (Fig. 3(c)), the two pillars of GHG emissions reductions in this study. Note that pathways with higher electrification rates require more electricity supply, so even though the ZCP dips initially in some LowLCOE pathways and in GT20 between 2030 and 2040, the average renewable electricity supply (Fig. 3(d)) never does.

The differences between the LCOEs of the HighRE pathway and LowLCOE pathways grow at deeper GHG reductions, even as the differences in ZCP shrink. This phenomenon is attributed to exponential growth in costs at very high ZCPs, primarily driven by rapid growth in renewable energy curtailment and battery storage capacity, as has been shown in previous work [19]. Peak loads are the last ones to be met by wind and solar power, and thus require dispatchable resources, modeled here as gas-based generation (which produces GHG emissions) or battery storage (which is relatively expensive when operating with low duty cycle). These dynamics are driven by ZCP and are thus largely independent of the amount of new end-use electrification.

In Fig. 3, the GT20 pathway keeps LCOE significantly lower than the HighRE_PS through more rapid electrification of building and vehicles than growth in ZCP. Fig. 3(d) shows that all pathways include a large increase in the total supply of renewable energy, but the LowLCOE paths have a lag in RE buildout vis-à-vis electrification. For example, the average total RE supply in 2030 in the HighRE_PS pathway (14.5 GW) is computed to occur around 2038 in the GT20 pathway. Note that this lag in wind and solar supply is shorter along other computed LowLCOE pathways. Restricting the ability to build new gas turbines, as is the case in the NoNewGT pathways, leads to lower electrification rates, higher ZCPs, and higher computed LCOEs after 2030 when compared to the GT20 pathway.

The ability to cost-effectively manage peak loads via peak shaving reduces overall electricity supply costs among the LowLCOE pathways.

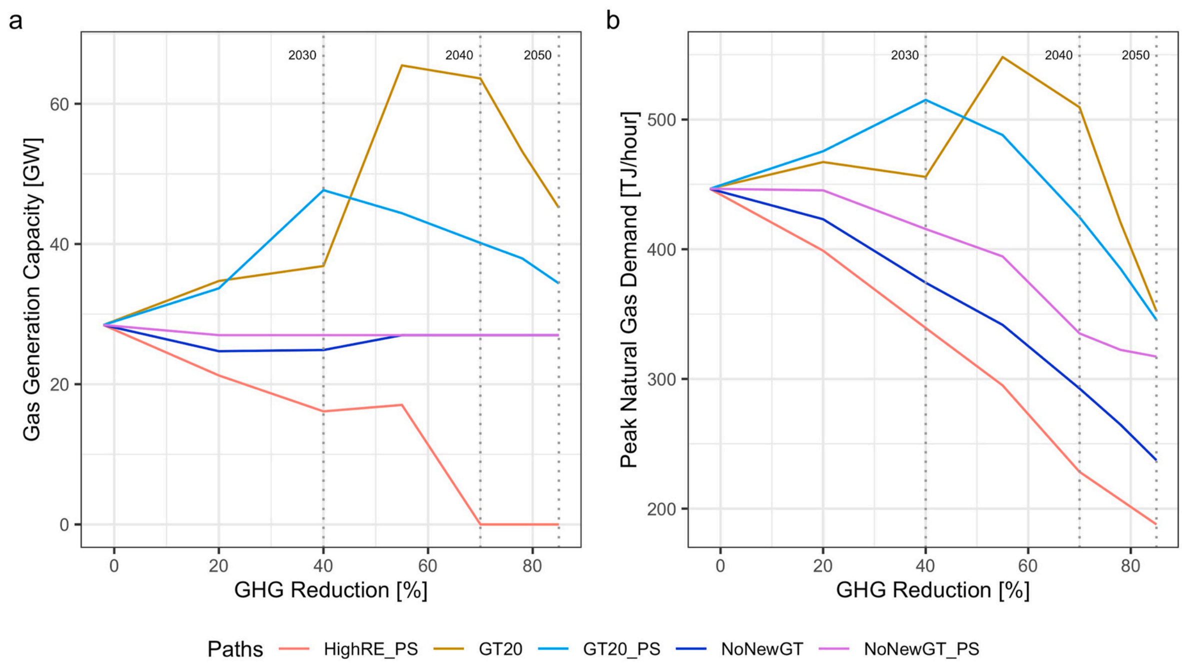

Fig. 4. | NYS decarbonization pathways showing (a) gas generation capacity, (b) maximum statewide natural gas demand. "GT20" indicates 20-year GT capital cost annualization; "PS" indicates scenarios with peak shaving.

By avoiding large, infrequent peaks associated with deep penetration of EHPs, approximately $8–10/MWh reductions in LCOE are computed at all stages in the decarbonization pathways. The LCOE reductions are significant considering that peak shaving only reduces the annual electricity demand by 1.4% even with 100% electrification; the cost reductions are driven by the 29% lower peak electricity demand (see Fig. 1) and maintaining high gas generator capacity factors (see Fig. S6). Moreover, pathways applying peak shaving (GT20_PS, NoNewGT_PS) keep LCOEs even lower than the current LCOEs in the short-term, benefitting from higher gas generator capacity factors than current values and better utilization of existing facilities.

Further details of the NYS natural gas system are shown in Fig. 4. Fig. 4(a) shows that unrestricted LowLCOE systems require substantial gas generation capacity even when achieving 85% GHG reductions. Scenarios with PS encourage more aggressive electrification while reducing the new GT buildout from the pathways without PS: While the GT20 pathway shows 65 GW of computed gas generation capacity in 2035, the GT20_PS pathway contains only 48 GW of capacity in 2030. The substantial new GT capacities correspond to increases in maximum natural gas demand. Both the GT capacity and peak natural gas demand decrease after an initial buildout in GT20 and GT20_PS scenarios, indicating the importance of investigating restrictions on that buildout even absent directed policy. In scenarios that do not allow new GT capacity (NoNewGT and NoNewGT_PS), there is no increase in statewide peak natural gas demand.

Although building electrification reduces the overall fossil fuel usage, the peak shaving method modeled here still requires end-use natural gas consumption. Fig. 4(b) shows that the GT20 pathway creates a sharp peak in natural gas demand between 2030 and 2040, reaching a peak that is 23% larger than the computed current peak; implementing peak shaving per the GT20_PS pathway also increases peak natural gas demand by 15%, though more modestly and in the nearer term. These results indicate that gas infrastructure capacity could be manageably reduced while still allowing limited use of fossil fuels to address peak heating needs in the transition.

Analyses of decarbonization pathways through 2050 with (1) an 8-year annualization period for new gas turbine capacity, and (2) limits placed on natural gas consumption are presented in Supplementary Figs. S4 and S5. Scenarios with lower cost assumptions for new energy infrastructure are also examined in the Supplement; while these simulations yield lower system costs, they do not change the relationships between the pathways or any key findings explored here.

3.2. Closer inspection of 2030 decarbonization scenarios

To better understand the effect on system and policy constraints on near-term system needs in the decarbonization pathways, Section 3.2 investigates individual scenarios corresponding to 2030. Fig. 5 shows total annual electricity supply and distribution upgrade cost breakdowns and the supply LCOEs (excluding distribution upgrade costs) of the selected pathways in 2030, along with costs and LCOE of the current scenario. Annual costs shown are for only the electricity (and not the gas system); these costs are driven by the need to supply new load with electrification and by the per unit cost of meeting the total electric load (i.e. the LCOE). Among these 2030 scenarios, the differences in total annual electricity costs are smaller than the differences in LCOE. For example, HighRE_PS and NoNewGT_PS pathways have almost the same total annual electricity costs while LCOE differs by 26%; that is, approximately the same total annual investment provides 22% more electricity (see Table 3). Baseload generation costs are marginally higher than the current value because of costs associated with the Hydro-Quebec electricity import project scheduled to come online by 2025, and transmission costs remain nearly constant even after electrified loads are added; the major cost differences stem from the other three categories.

Fig. 3 shows that a tradeoff exists between prioritizing electrification or zero-carbon electricity to meet the same GHG emissions reduction targets. This tradeoff reflects divergent allocation scenarios towards either gas generation and distribution upgrades (prioritizing electrification) or renewable & storage (prioritizing zero-carbon electricity) for similar total annual costs. Peak shaving reduces peak loads substantially, and counterintuitively increases the investments in distribution system upgrades. Here peak shaving pathways lower emissions cost-effectively by allowing higher electrification rates that in turn lower LCOE in 2030.

For further comparison, Table 3 presents HighRE_PS, GT20_PS, and

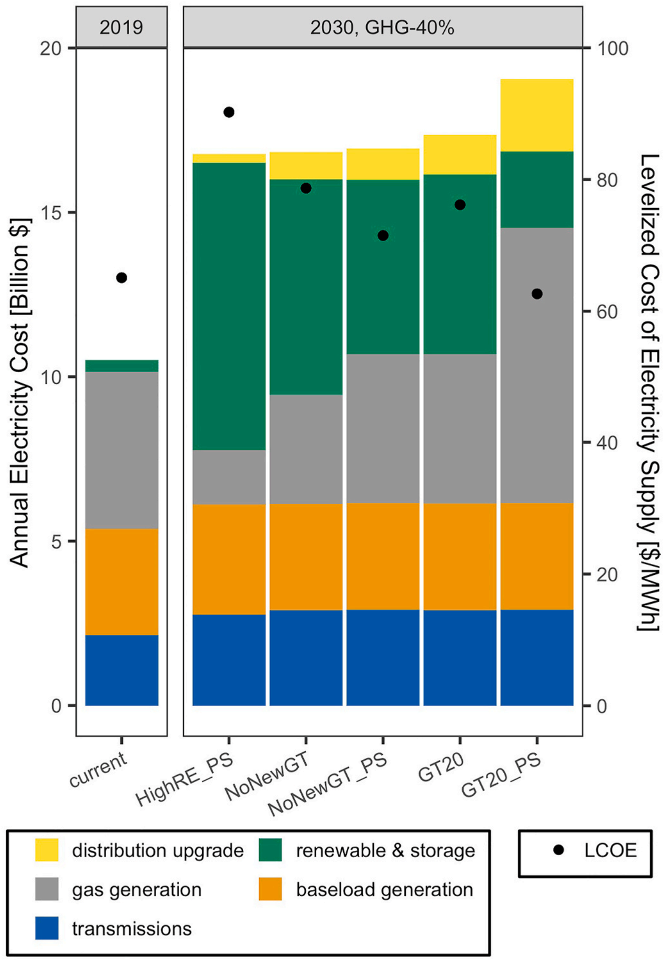

Fig. 5. | Sectoral annualized cost of electricity supply (bars, left y-axis) and levelized cost of electricity (LCOE) supply (points, right y-axis) of different New York State decarbonization pathways. "GT20" indicates 20-year GT capital cost annualization; "PS" indicates scenarios with peak shaving. Results are shown for the current grid system and pathway results corresponding to 2030. In the cost categories, "distribution upgrade" represents the demand-side distribution expansion costs due to electrification; "renewable & storage" represents all costs related to onshore and offshore wind, utility-scale solar, utility-scale battery; "gas generation" represents all costs related to fossil fuel generation; "baseload generation" represents all costs related to nuclear, hydropower, imported hydropower, and biofuel generation.

NoNewGT_PS pathway results with and without the nodal peak gas consumption constraint imposed. The HighRE_PS case contains 87% zero-carbon electricity supply in 2030 and a model-selected 25% electrification rate to achieve a 40% emissions reduction. For this pathway, LCOE is computed as $90/MWh – $25/MWh higher than the computed current value – primarily driven by 43 GW of required wind and utility-scale solar power. In comparison, GT20_PS achieves 100% electrification and invests in a small amount of renewable generation to minimize the LCOE. Peak loads of 59 GW induced by electrification are met primarily by 21 GW of new GT capacity. The third scenario, NoNewGT_PS, avoids both the high cost of HighRE_PS and the large new GT capacity of GT20_PS. Its electrification rate is approximately midway between the HighRE_PS and GT20_PS scenarios, and the installed wind and solar capacity is midway between the current and the HighRE_PS scenario.

Table 3 also examines the consequences of limiting future natural gas demands to the modeled current peak gas demand as a proxy for no new gas pipeline capacity. Limiting peak natural gas demand reduces gas generation capacity by 9 GW in the GT20_PS pathway in 2030, with correspondingly lower electrification rates and an acceleration of renewable generation installation. In all cases, the effect of limiting peak gas demand on LCOE is small, at most $3/MWh, with slightly less model-selected electrification and slightly higher ZCP, per Supplementary Fig. S4.

3.3. *Assessing the impact of heterogeneous electrification rates*

The decarbonization pathways presented previously assume equal electrification rates for buildings and vehicles and assume that these rates are the same across all nodes ("uniform rates"). Section 3.3 presents 2030 scenario results without this constraint applied ("heterogeneous rates"). Results are compared in Table 4 for the NoNewGT_PS pathway, as it computes reasonable electrification rates between those specified for the HighRE_PS and GT20_PS pathways. At the state level, the heterogeneous rates scenario selects similar ZCP and renewable electricity capacities, and almost the same LCOE. When applying peak shaving, the model electrifies more buildings than vehicles because buildings yield greater GHG reductions per-MW of additional load (see Supplementary Section S1.3.3) and peak shaving for electrified space heating mitigates new dispatchable generation needs, but both building and vehicle electrification rates are not far from the 60% in the uniform rates scenario. Nevertheless, an exploration of optimal electrification rates by node reveals different preferences across NYS.

As shown in Table 4, downstate Nodes 3 and 4 select higher rates of building electrification than upstate Nodes 1 and 2, although the distribution upgrade costs of the former nodes are up to six times that of the latter. Downstate nodes benefit from higher average winter temperature and fewer intense cold weather events, which lead to lower peak requirements for electrified space heating. Lower peak loads lead to better capacity factors of dispatchable resources and lower per-MWh costs of upgraded distribution. Supplementary Fig. S2 bolsters this finding, showing that the current summer electricity peak is approximately 50% higher than the current winter peak in downstate nodes, providing considerable load and distribution capacity to electrify the space heating sector in winter. In contrast, the current summer and winter peak differences in upstate nodes are only about 20%. Compared to the building sector, vehicle electrification induces lower load peaks and has smaller

Table 3
2030 scenarios (40% GHG emissions reduction) for select decarbonization pathways with or without peak natural gas flow limit.

Year/Scenario	Pathway	Avg Load [GW]	Peak Load [GW]	Zero-carbon Percentage [%]	Electrifica tion Rate [%]	Utility Solar + Wind Capacity [GW]	Battery Capacity [GW][b]	Gas Generator Capacity [GW]	LCOE [$/MWh]
2019	Current	18.7	33.9	38	0	2.0	0.03	28.4[c]	65.1
2030 – Without Gas Limit	HighRE_PS	21.8	36.4	87	24	43.3	9.1	16.1	90.2
	GT20_PS	31.6	58.8	32	100	10.6	5.3	47.7	62.6
	NoNewGT_PS	26.5	44.2	54	60	22.4	10.7	27.0	71.5
2030 – With Gas Limit[a]	GT20_PS	29.6	53.0	39	84	17.9	7.9	38.5	65.6

[a] The peak natural gas flow limit has limited statewide impacts on HighRE_PS and NoNewGT_PS pathways, so only the illustrative GT20_PS pathway is shown.
[b] This paper assumes the battery power-to-energy ratio of 0.25 kW/kWh (i.e., 4-h battery systems).
[c] Includes 1.4 GW capacity beyond current 27.0 GW to account for model excluding existing fossil fuel-based imported electricity.

Table 4
“NoNewGT_PS” scenario results in 2030 after allowing heterogeneous nodal electrification rates (each node may have different electrification rates for buildings and vehicles).

Statewide result summary

Electrification Constraints	GHG reduction [%]	Zero-carbon percentage [%]	Building Electrification rate [%]	Vehicle Electrification rate [%]	Utility Solar + Wind Capacity [GW]	Battery Capacity [GW]	Gas Generator Capacity [GW]	LCOE [$/MWh]
Heterogeneous rates	40	55	65[a]	48[b]	22.4	9.7	27.0	71.3
Uniform rates	40	54	60	60	22.4	10.7	27.0	71.5

Nodal electrification rates

	Building electrification rate [%]				Vehicle electrification [%]			
	Node 1	Node 2	Node 3	Node 4	Node 1	Node 2	Node 3	Node 4
Heterogeneous rates	54	26	81	91	100	70	0	0
Uniform rates	60							

[a] Nodes have different building electrification rates. And the statewide building electrification rate is the ratio of the fossil fuel thermal energy reduced by electrification to the total thermal energy that is able to be electrified in the building section.
[b] Same as the building section.

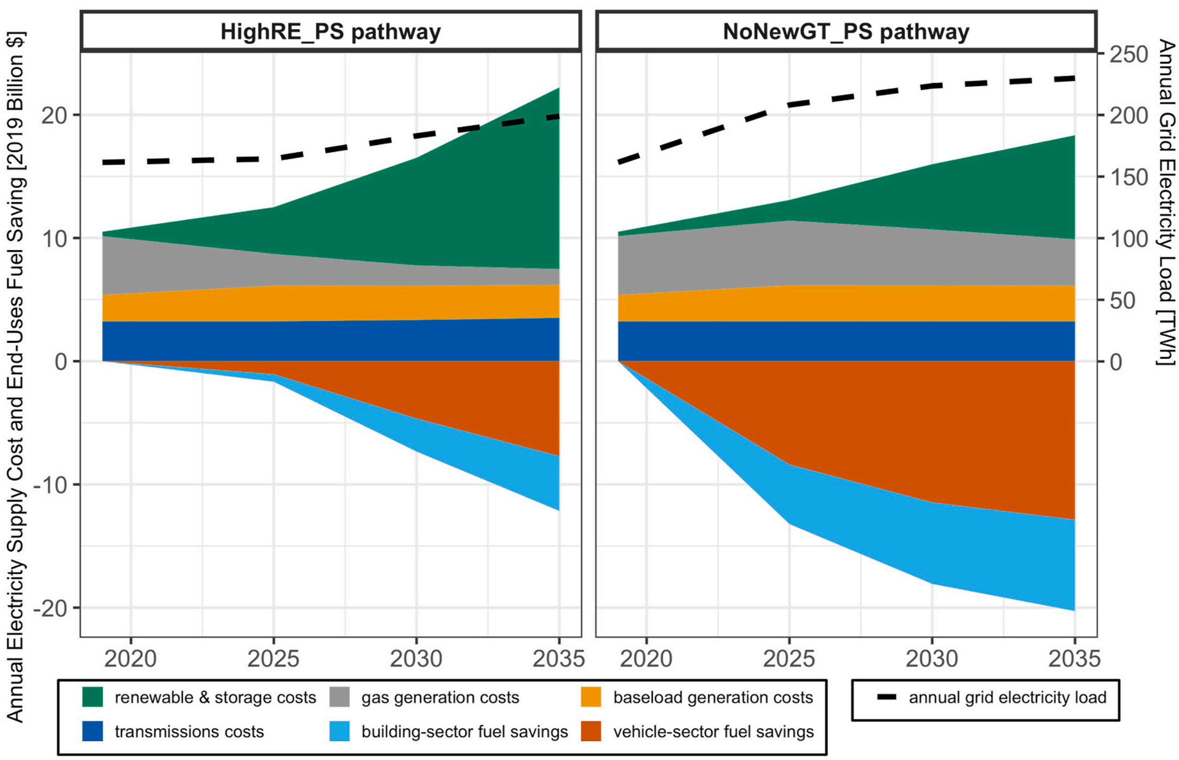

Fig. 6. | Annual electricity supply cost and end-uses fuel cost saving (area chart, left y-axis. Supply cost as positive and savings as negative) and annual grid electricity load (dashed line, right y-axis) from 2019 to 2035 of New York State HighRE_PS and NoNewGT_PS pathways. End-Uses electrification increases electricity load as well as decreases directly fossil fuel consumption. In the cost categories, “renewable & storage” represents all costs related to onshore and offshore wind, utility-scale solar, utility-scale battery; “gas generation” represents all costs related to fossil fuel generation; “baseload generation” represents all costs related to nuclear, hydropower, imported hydropower, and biofuel generation; “building-sector fuel” represents propane, fuel oil, and natural gas in building sector; “vehicle-sector fuel” represents diesel and gasoline in vehicle sector.

impacts on nodal load factors (shown in Supplementary Fig. S2), and electrified vehicle load differences between nodes are small. In Table 4, upstate nodes with lower distribution upgrade costs electrify more vehicles while downstate nodes have no vehicle electrification.

The Supplementary Information includes additional sensitivity analyses. Notably, there are slight differences in installed nodal renewable capacity in the heterogeneous rates scenario for the NoNewGT_PS pathway (Supplementary Table S13). In addition, when considering no peak shaving technology, Supplementary Table S14 shows that the NoNewGT pathway selects higher statewide vehicle electrification rates and lower statewide building electrification rates compared to the NoNewGT_PS pathway. However, the nodal end-use priorities discussed above remain substantively the same.

4. Discussion

As required in CLCPA, the existing NYS studies (such as [24]) typically consider specified GHG emissions reduction targets and specified ZCP targets. Therefore, HighRE group of NYS decarbonization pathways in this paper is modeled with both targets. Besides, this paper also models a LowLCOE group of pathways achieving GHG targets without ZCP targets, inspired by the consideration that accelerating electrification rather than ZCP could achieve the same GHG emissions with lower LCOEs [19]. Our findings show consistency with this consideration, through drawing these two groups of pathways. Furthermore, to better understand the role of electrification induced peak loads and gas infrastructure constraints on decarbonization pathways and fill the gaps in the literature, we examine the implications of four choices on pathways: peak shaving for electrified space heating demand (with limited use of fossil fuels in existing heating systems); limits on new GT capacity; limits on nodal and statewide peak natural gas demand; and heterogeneous nodal building and vehicle electrification rates. The comparisons between these pathways are not only meaningful for decarbonization in NYS, but also have universal value for different regions with renewable portfolio standards, potential increasing peak loads due to electrification, and gas infrastructure constraints. In this section, we provide further interpretation of the paper findings.

In a region such as New York State with massive heating demands, the peak load at 100% electrification could increase from a current level of 34 GW–83 GW (see Fig. 1 (a)), assuming current building envelopes and energy efficiency. Because the largest heating-driven peak loads are infrequent, the results show that peak shaving improves the system load factor significantly through a 29% peak load reduction while only decreasing average load by 1.4% at 100% electrification. The small decrease in the average load reflects that the load could be potentially met with back-up fuels, and even if met with natural gas the emissions impacts would be small. Peak shaving would mitigate the buildout of dispatchable generation capacities and maintain higher utilization. In this paper, we examine the benefits of shaving peaks due to electrification using a dual source-heating model, where on-site gas is used to meet non-electrified peaks. Peak shaving could also be achieved by other methods such as improving building efficiency [30] and deploying domestic solar and battery system [35] or through the use of renewable fuels.

With peak shaving applied, the illustrative pathways are clearer. To meet the 40% GHG reduction target for 2030, the GT20_PS scenario achieves full electrification of buildings and vehicles in the next decade – requiring 11 GW of wind and utility-scale solar capacity and 21 GW of new gas generation capacity – and leads to a slight LCOE decrease from the current value of $65/MWh to $63/MWh. The pathway that does not permit new GT capacity (NoNewGT_PS) meets emission targets through a 60% electrification rate and somewhat higher ZCP with nearly doubled wind and solar capacity, resulting in an LCOE of $72/MWh. Both these scenarios lead to significantly lower LCOEs compared to the $90/MWh in the 2030 HighRE_PS scenario where the 40% emissions reduction target and 70% renewable target are met. Additionally, another gas constraint that limits peak natural gas demand does not significantly increase LCOE in all cases, suggesting that existing gas pipelines may be adequate for future supply in NYS.

The GT20_PS pathway has the lowest LCOEs, but there are some practical implementation concerns for this pathway. Achieving 100% electrification in 10 years may not be realistic, raising the possibility of stranded GT and pipeline capacity expansions that would face approval hurdles in the first place. In contrast, the NoNewGT_PS avoids new GT buildouts and lowers the pace of electrification, making implementation more likely. In Section 3.2, we found that NoNewGT_PS and HighRE_PS pathways have similar annual costs for electricity supply. However, the former has higher electricity demand due to building and vehicle electrification, which corresponds to fossil fuel consumption savings for consumers. To quantify these cost savings as a post-processing step (i.e., a step that has no impact on the model results), constant fuel prices[3] are applied to fossil fuel consumption in building and vehicle sectors after electrification from the model results, and compared to the current total fossil fuel costs on buildings and on-road vehicle. Equations are introduced in Supplementary Material section S1.3.14.

Fig. 6 presents the estimated annual cost of electricity supply costs broken into four categories: renewable and storage, gas generation, baseload generation, and transmissions. The figure also shows, as negative numbers, the estimated annual potential savings from lower fossil fuel consumption due to building and vehicle electrification for the HighRE_PS and NoNewGT_PS pathways between 2019 and 2035. The results indicate that these two pathways have similar electricity supply costs if integrating over the 17-year period (HighRE_PS – $15.0B/year; NoNewGT_PS – $14.3B/year on average). While one pathway invests more in renewable generation and battery installation, the other spends more on gas generation (see Section 3.2). However, in this period, the grid electricity supply for the HighRE_PS and NoNewGT_PS pathways is 175 and 207 TWh (annual averages over 17 years), respectively.

Using Fig. 6, we can synthesize the overall techno-economics of the NoNewGT_PS pathway over the 17-year period compared to the current scenario (modeled for 2019). Currently, the total electricity supply costs are $10.5B, and the total fossil fuel costs on building and vehicle sectors are $30.6B. In the NoNewGT_PS pathway, the 45 TWh higher annual load on average from electrification results in an additional $3.8B/year of electricity supply; whereas it means 8.4×10^8 $GJ/year$ of fossil fuel energy savings or $13.2B/year cost savings on average from building and vehicle sectors. Moreover, the distribution upgrade costs are about $0.7B/year (not shown in this figure). Hence the savings compared to the current scenario add to about $148B over 17 years from 2019 to 2035 for the NoNewGT_PS pathway. In contrast, when compared to the 2019 scenario, the end-use fuel cost savings of the HighRE_PS pathway are almost equal to the increment of electricity supply costs.

A policy question is whether these savings would pay for the costs not accounted here: (1) consumer-side capital expenditure costs in upgrading their current equipment to electric heat pumps and electric vehicles; (2) investments in public charging infrastructure; (3) utility costs of retaining last-mile gas distribution infrastructure to allow peak shaving. There are no vetted studies of these costs since they are very difficult to estimate. With 67% electrification in the NoNewGT_PS pathway by 2035, we estimate that roughly 1.2B Square of floor area would need a retrofit and about 7 million vehicles would become electric. These estimates then lead to a rough estimate of $60B for buildings and $35B for vehicles in NYS, a total of $95B. These rough estimates are for simple capital costs without the cost of capital and any other added replacement costs between 2019 and 2035. The fuel savings to 2035 of $148B is comparable and can potentially pay for the added aggregated consumer side costs of electrification in the NoNewGT_PS pathway.

This discussion is considerably idealized and stylized compared to reality. For example, utilities might want to recover more than the cost of electricity supply and the cost of distribution upgrades; maintaining gas supply while reducing gas usage might imply much higher costs for the supplied gas; during the transition due to electrification-installation and maintenance costs could become high due to supply chains and

[3] For the whole of New York State, use 2019 average prices of the Middle Atlantic region in the US [$/MMBtu]: propane for residential – 21.37; distillate fuel oil for residential – 21.89; natural gas for residential – 10.40; propane for commercial – 17.53; distillate fuel oil for commercial – 21.97; natural gas for commercial – 7.52; gasoline for vehicle – 22.17; diesel for vehicle – 22.11 [36].

skills.

Lastly, for the scenarios allowing heterogeneous nodal electrification rates of building and vehicle, the degree of electrification may show greater nodal differences than are likely. However, the model does reveal that electrification induced winter peak loads relative to current summer peaks are geography-specific and the primary drivers behind an optimal electrification strategy, especially for the building sector. This has clear implications for electrification planning strategies for regional systems, which generally have heterogeneous load densities and climates. For New York State, the results dispel the concerns that nearly six-fold higher costs of distribution upgrades in downstate areas compared to upstate areas would hinder the electrification process in downstate nodes.

5. Conclusion

This paper applies the System Electrification and Capacity TRansition model formulated for the New York State (NYS) energy system (SECTR-NY) to a set of potential pathways to achieve specified greenhouse gas (GHG) emissions reduction policy targets from the three dominant energy sectors (electricity generation, buildings, and vehicles). A subset of "HighRE" pathways include targets for both GHG emissions reduction and zero-carbon electricity percentage (ZCP); another set of "LowLCOE" pathways prescribe GHG targets but not ZCPs. Compared to HighRE pathway results for the same GHG emissions reduction targets, LowLCOE pathways prioritize early electrification, resulting in significantly lower LCOEs. While the LowLCOE and HighRE pathways have similar total annualized electricity supply costs by 2035, the electricity demand of the LowLCOE pathways is higher. This results in fossil fuel cost savings on building and vehicle sectors of LowLCOE pathways, which can provide incentives for higher electrification. We also examine the implications of four choices on pathways in this paper. Firstly, peak shaving mitigates the effects of electrification on peak loads and reduces LCOEs significantly by about $8–10/MWh at all stages of the LowLCOE pathways. Compared to the pathway that permits new gas turbine (GT20_PS) with aggressive electrification and large new gas turbine capacities, the pathway that does not permit new gas turbine (NoNewGT_PS) is more feasible, albeit with the trade-off that this leads to higher LCOEs. However, these LCOEs are still significantly lower than the LCOEs of HighRE pathways. Lastly, the constraint that limits peak natural gas demand or allows heterogeneous nodal electrification rates, does not significantly increase LCOE.

The full suite of energy system planning and technology considerations is difficult to represent quantitatively; hence, these results should be taken as an aid to policymaking and not as definitive, deterministic pathways. For long-term simulations such as in 2050, it is worth noting that technology costs will evolve over time, and breakthroughs may happen in dispatchable zero-carbon electricity generation and very low costs energy storage. These are not considered in this paper. The other limitation of this study is that we examine the trade-off between zero-carbon electricity and electrification progress with modeled parameters, only by investigating the electricity grid side but not the consumer side. Further research considering (1) consumer costs of electrification; (2) additional costs of specific peak shaving measures; (3) total electricity costs and fossil fuel costs on consumers, will provide better understanding of this topic.

Credit author statement

Y.W., **M.W.**, **T.C.**, and **V.M.** conceived of the study and discussed the results, which was led by **V.M. Y.W.**: Methodology, Computation, Visualization, Paper Draft. **M.W.**: Methodology, Paper Draft, Paper editing. **T.C.**: initial model, Paper editing. **V.W.**: Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code and data used can be found at the "nys-pathways" branch in the "https://github.com/SEL-Columbia/sectr-ny.git" repository. And the numbers shown in the figures could be found in "paper-figures-data.xlsx" in the same repository.

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Appendix A. Supplementary data

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