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Transportation emissions scenarios for New York City under different carbon intensities of electricity and electric vehicle adoption rates

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Abstract

Like many cities around the world, New York City is establishing policies to reduce CO_2 emissions from all energy sectors by 2050. Understanding the impact of varying degrees of electric vehicle adoption and CO_2 intensities on emissions reduction in the city is critical. Here, using a technology-rich, bottom-up, energy system optimization model, we analyse the cost and air emissions impacts of New York City's proposed CO_2 reduction policies for the transportation sector through a scenario framework. Our analysis reveals that the electrification of light-duty vehicles at earlier periods is essential for deeper reductions in air emissions. When further combined with energy efficiency improvements, these actions contribute to CO_2 reductions under the scenarios of more CO_2-intense electricity. Substantial reliance on fossil fuels and a need for structural change pose challenges to cost-effective CO_2 reductions in the transportation sector. Here we find that uncertainties associated with decarbonization of the electric grid have a minimum influence on the cost-effectiveness of CO_2 reduction pathways for the transportation sector.

Cities around the world are challenged with the environmental consequences of urbanization, population growth and motorization. Transportation demand accounts for 25% of the energy delivered globally[1]. In the United States, on-road vehicles represent 31% of the total delivered end-use energy in 2017 (ref. 2). New York City (NYC) is tackling notable growth in travel demand[3]. Although the average vehicle miles travelled per person is nine miles per day for NYC, which is approximately one-third of that of other large metropolitan areas in the United States[4,5], and the public transit system is the largest in the United States[6,7], the transportation sector still contributes to air quality issues[8] and endangers the health of NYC residents[9,10,11]. Furthermore, NYC's transportation sector contributes 28% of total greenhouse gas emissions by end-use sectors[12], with private vehicles and

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Data availability

The data that support the plots in the manuscript are available at US EPA's ScienceHub Data Repository (https://catalog.data.gov/dataset). Source data are provided with this paper.

Ethics declarations

Competing interests

The authors declare no competing interests.

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trucks being the major contributors (83% and 13%, respectively)[13]. Recently, NYC has implemented a target to reduce greenhouse gas emissions by 80% by 2050 (referred to as the 80 × 50 target)[14].

While many current bottom-up optimization models capture the transportation sector with a high level of detail for technology and fuel choices, studies acknowledge the need to better understand and capture urban versus rural considerations[15,16,17,18]. There is a gap between place-based research reflecting the dynamics between transport mode and urban pollution, and global models emphasizing technology efficiency, fuel choice and emissions reductions of policies at an aggregate level. The application of the City-based Optimization Model for Energy Technologies (COMET) to NYC facilitates greater spatial resolution and allows one to evaluate non-light-duty vehicle modes (for example, subway and buses). Leveraging an energy system approach identifies potential emissions trade-offs between sectors (for example, a transportation sector policy leads to disbenefits in the buildings sector or vice versa) as well as across transport modes (for example, between light-duty vehicles and public transit).

We assess fuel and technology switching effects across transportation modes, driven by a range of assumptions for the CO_2 intensity of electricity. Using COMET[19], a partial-equilibrium, technology-rich energy–environment–economy optimization model, we analyse the cost and emissions implications of alternative technology investment decisions in end-use sectors. We then evaluate the robustness of those decisions under future uncertainties for the electric grid mix to achieve the 80 × 50 target. We show that a scenario with high CO_2 intensity for the electric grid (DEPENDENCE) resulted in earlier investments in energy efficiency, fuel switching and electrification across multiple transport modes. In particular, converting diesel buses to electric and switching from diesel to compressed natural gas (CNG) for heavy-duty short-haul freight results in deeper reductions of NO_x and particulate matter with a diameter 10 micrometres or less (PM_{10}). In the absence of electrification or potential light-duty demand increases, we observe that efficiency measures and fuel switching, specifically in buses and medium- and heavy-duty trucks, resulted in a robust strategy to lower both CO_2 and other air pollutants. The results highlight the importance of early action, specifically targeting efficiency improvement and fuel switching rather than the electrification of only light-duty vehicles. Early action also results in air emissions co-benefits. From a cost perspective, the scenarios with high CO_2 intensity (DEPENDENCE) result in lower energy system costs compared to low CO_2 intensity (REVOLUTION) counterparts.

Transportation pathways scenario design

New York City's Roadmap to 80 × 50 lays out specific plans to reduce CO_2 emissions from the energy, buildings, transportation and waste sectors. The transportation emissions reductions (58% and 82% from 2005 levels by 2030 and 2050, respectively)[14,20,21] can come from mode shifts such as increased biking and walking, reduced light-duty demand, fuel switching and fleet turnover to more efficient vehicles. NYC assumes the CO_2 intensity of electricity will follow New York State's Clean Energy Standard, mandating at least 50% of state's electricity generation coming from renewable resources by 2030 (ref. 22).

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We used COMET-NYC19 to evaluate scenarios of transportation technology and fuel choices to achieve the 80 × 50 target. The STEADY-STATE scenario presents business-as-usual trends in technology adoption and fuel consumption in end-use sectors without any specific CO_2 reduction goal. The policy scenarios (DEPENDENCE and REVOLUTION) capture the uncertainty in the speed of New York State's electricity grid decarbonization[22] on achieving the 80 × 50 target and implications for the transportation sector. In DEPENDENCE, New York State fails to achieve reductions in the CO_2 intensity of electricity[22], whereas in REVOLUTION, the state's Clean Energy Standard[22] is met. The 80 × 50 target in DEPENDENCE and REVOLUTION is modelled via an upper bound constraint for in-city CO_2 emissions associated with fuel and electricity consumption between 2025 and 2050. Our goal is to demonstrate the sole impact of fuel and technology choices; therefore, transportation mode shares and demands are held constant in the STEADY-STATE, DEPENDENCE and REVOLUTION scenarios.

To capture the effect of demand shifts due to the changes in how people and goods move, we perform a sensitivity analysis on light-duty vehicle demand reduction strategies proposed by NYC (the MODESWITCH scenario variant). MODESWITCH variants of DEPENDENCE and REVOLUTION scenarios are called DEP_MODESWITCH and REV_MODESWITCH, respectively. We also explore the impact of more aggressive light-duty electrification (the BATTERY scenario variant) and increased use of ride-hailing services provided by transportation network companies (TNCs; the TNC scenario variant)[3]. Figure 1 illustrates the COMET-NYC structure, while the Methods describe the model and scenario design.

Energy, technology and emissions trends in STEADY-STATE

In 2010, gasoline was the main fuel meeting the light-duty demand (80% of total fuel consumption; Figs. 2 and 3d), whereas diesel was mainly consumed by buses and heavy-duty short-haul vehicles (Fig. 3a). Ten percent of the energy consumption in the transportation sector is attributed to the public transit system (that is, the subway). Although, this is much higher than the US average of 0.3% (ref. 23), in the aggregate city-wide electricity consumption, it only corresponds to five percent of the total (Fig. 2). By 2050 under this scenario, light-duty demand is met by 36% less gasoline despite the increase in vehicle miles travelled. A decrease in fuel consumption yields reductions for CO_2. Although an increase in CO_2 emissions is expected with population growth, urbanization and economic development, the implementation of national light-duty fuel efficiency standards[24,25] and vehicle turnover to more efficient technologies leads to reduced fuel consumption and therefore reductions in city-wide emissions (Supplementary Figs. 1 and 2a) and transportation CO_2 emissions (Fig. 4 and Supplementary Fig. 2b). Supplementary Note 1 provides additional results.

Transportation fuel switching also results in reduced air emissions impacting public health. The transportation sector is a major contributor to NO_x emissions, which leads to the formation of ozone. In 2010, 52% of the NO_x emissions were from the transportation sector, with the light-duty sector contributing 73% of these emissions (Fig. 5a and Supplementary Fig. 3). Across all scenarios, both city-level and transportation NO_x emissions decrease substantially beyond 2015 (Fig. 5 and Supplementary Fig. 4). With the implementation

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of national emissions standards[26,27,28], substantial reductions in transportation NO_x were observed in 2015 and beyond, but by 2050, transportation NO_x still contribute a considerable portion of total NO_x emissions in NYC, with the light-duty sector constituting more than fifty percent of the total.

Particulate matter emissions follow CO_2 reduction trends in the near term with one exception in heavy-duty short-haul trucks. In 2030, diesel trucks start to replace CNG-fuelled trucks because they are cheaper alternatives to CNG-fuelled technologies. This change results in a slight upward trend in PM_{10} emissions (Supplementary Figs. 5 and 6 and Supplementary Note 1.3 for in-depth PM_{10} discussion).

Trends under variations of carbon intensity of electricity

We observe a 79% and 83% reduction in gasoline consumption in REVOLUTION and DEPENDENCE with respect to STEADY-STATE, respectively. Electricity consumption increases by 33% and 26% for REVOLUTION and DEPENDENCE. In the near term, the DEPENDENCE scenario consumes more electricity in the transportation sector than other scenarios; however, for city-wide electricity consumption, DEPENDENCE has the lowest overall consumption (Supplementary Fig. 7a). Since CO_2 emissions savings were not coming from the electric sector, due to the higher CO_2 intensity of electricity in DEPENDENCE, the results showed more investments into cleaner fuels and energy efficiency technologies for buildings and transportation to achieve the 80 × 50 target. Supplementary Notes 1.2 and 2 provide additional power-sector-related discussion on STEADY-STATE, DEPENDENCE and REVOLUTION.

The city's goal for zero-emission vehicles is introduced into the model with a constraint that ensures at least 15% and 50% of all new light-duty vehicle purchases are zero-emission (battery) vehicles in 2030 and 2050, respectively. This constraint sets an overarching bound. Hence, the mix of vehicle classes (for example, full size, compact and small sport utility vehicle) within the battery electric vehicle fleet is determined by the model to satisfy the electrification constraints. The penetration of battery electric vehicles is not constrained for the rest of the modelling periods. The hybrid and plug-in hybrid vehicles are excluded from the constraints. We observe further electrification of light-duty vehicles in both REVOLUTION and DEPENDENCE going beyond the minimum electrification requirements for 2030 and 2050. Plug-in hybrid electric vehicles and battery electric vehicles have a higher penetration rate in DEPENDENCE than in REVOLUTION in the earlier periods. Despite a higher CO_2 intensity of electricity in DEPENDENCE relative to REVOLUTION, the model makes earlier investments in plug-in hybrid electric vehicles to meet the 80 × 50 target. In addition, the overall CO_2 intensity of transportation in DEPENDENCE is much lower with increased efficiency improvements in all car classes (Fig. 6g,l) compared to STEADY-STATE and REVOLUTION. By 2050, the electricity demand for light-duty vehicles reaches its highest levels in DEPENDENCE and REVOLUTION (Fig. 3e,f). Rail passenger demand in DEPENDENCE and REVOLUTION is the same; the rail electricity usage remains relatively constant over time, a 27.9% decrease from STEADY-STATE. Both DEPENDENCE and REVOLUTION introduce more efficient subway cars starting in 2025 that reduce the per-passenger electricity demand.

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Compared to light-duty vehicle and subway demand, bus demand is small; however, interesting fuel shifts are observed. In the long run, CNG replaces diesel in the bus fleet, and electrification starts around 2030 for REVOLUTION and DEPENDENCE. While not large on an energy-system-wide scale, this fuel switching in the bus fleet has local air emissions implications. Because the bus fleet is run by NYC, the implementation of fuel switching may be more viable and can influence changes in other modes. Here, we found that by 2050, DEPENDENCE mostly electrifies the bus fleet, while REVOLUTION relies equally on CNG and electricity. Heavy-duty short-haul vehicles rely primarily on fuel-efficient diesel technologies in the midterm, then shift more heavily to CNG in later model years. DEPENDENCE results in more utilization of CNG than REVOLUTION, as well as more fuel-efficient vehicles. By 2050, as a result of an increase of CNG use in heavy-duty short-haul trucks, the highest contribution of CNG occurs under DEPENDENCE (Fig. 3b). Diesel consumption, under both REVOLUTION and DEPENDENCE, drops substantially, with deeper reductions under DEPENDENCE (Fig. 3b,c). Use of CNG in buses and heavy-duty trucks (mostly waste collection trucks) is already prevailing across the nation, and our findings are consistent with the trends observed in the city's municipal operations.

Figure 4 illustrates the transportation CO_2 emissions by mode for STEADY-STATE and changes observed in DEPENDENCE and REVOLUTION with respect to STEADY-STATE. DEPENDENCE results in more cumulative CO_2 emissions reductions when compared to REVOLUTION (Supplementary Fig. 2). Most of these reductions were observed in the light-duty sector, followed by short-haul trucks in the heavy-duty sector.

Furthermore, deeper NO_x reductions are observed in DEPENDENCE due to the earlier switch to newer and more fuel-efficient cars as well as plug-in hybrid electric vehicles (Fig. 5). We observe the use of CNG vehicles in REVOLUTION resulting in a slight increase in NO_x emissions in the near term up until 2030 (Supplementary Tables 1–5 present the emission factors for fuels). Interestingly, increased reliance on CNG and electricity reduced NO_x emissions, as the NO_x emission factors for CNG are much lower for diesel and higher for gasoline.

Implications of increased light-duty vehicle electrification

Electric vehicles are considered an integral part of decarbonization scenarios. Recent trends in the pace of light-duty electrification highlight important uncertainties as the transportation system changes. Thus, we investigated the impact of additional light-duty electrification on the DEPENDENCE and REVOLUTION scenarios (Methods and Supplementary Note 3). In the BATTERY variant of DEPENDENCE and REVOLUTION (called DEP_BATTERY and REV_BATTERY, respectively), we simulate a case where NYC's declared electrification targets for light-duty vehicles (Table 1) are doubled through introducing a constraint into the model. The constraint is designed to satisfy at least 30% and 100% of light-duty vehicle purchases being battery electric vehicle (excluding plug-in hybrids and hybrid vehicles) in 2030 and 2050, respectively. Other modelling periods are not constrained.

The BATTERY scenarios revealed even deeper CO_2 cumulative reductions, with DEP_BATTERY having the deepest reduction (Supplementary Fig. 9a). Fifty-two percent of

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light-duty vehicle miles travelled are met by more highly efficient cars in DEP_BATTERY (Fig. 6h) than REV_BATTERY in 2030 (Fig. 6j). Furthermore, we observe a higher percentage of battery electric vehicles (36%) in DEP_BATTERY in 2030, which highlights the key role of transportation electrification despite the lack of reduced electric sector CO_2 emissions beyond 2030. With perfect foresight (in each period, the model makes investment decisions with the full information of all future events including the consequences of those investment decisions within the modelling horizon), COMET-NYC finds investment in energy efficient and electric cars in earlier modelling periods more beneficial to reduce overall CO_2 levels, despite the higher CO_2 intensity of electricity. In REVOLUTION, by 2050, a higher percentage of light-duty vehicle miles travelled is met by plug-in electric vehicles and battery electric vehicles compared to DEPENDENCE (Fig. 6n,l). However, with the addition of BATTERY sensitivity, the electrification constraint forces the system to utilize full battery electric vehicles instead of hybrid and plug-in hybrid options in both DEP_BATTERY and REV_BATTERY (Fig. 6m,o).

Emissions implications of future transport mode changes

Emerging trends such as increased use of ride-hailing services (TNCs) or behavioural changes leading to higher public transit usage contribute to the uncertainties in how future transportation demands might change. We model TNC variations of the DEPENDENCE (DEP_TNC) and REVOLUTION (REV_TNC) scenarios where switching from public transit to more ride-hailing increases light-duty demand (Methods for underlying assumptions). These demand shifts lead to 57% and 10% increases in light-duty fuel consumption in 2050 in scenarios DEP_TNC and REV_TNC, respectively, compared to DEPENDENCE and REVOLUTION (Supplementary Fig. 8). This increase in fuel consumption reduced the savings in NO_x emissions by 6% in DEP_TNC compared to DEPENDENCE and by 12% in REV_TNC compared to REVOLUTION (Fig. 7). We also we observe reduced emissions savings for PM_{10} and CO_2 in DEP_TNC and REV_TNC relative to DEPENDENCE and REVOLUTION (Supplementary Figs. 5 and 9, respectively). Distinct patterns in light-duty vehicle fuel consumption emerge. For example, DEP_TNC accelerates investment in newer cars with lower emissions rates and increased fuel efficiency, yielding a 6% reduction in NO_x emissions savings in the near term with respect to DEPENDENCE. REV_TNC results in the smallest reductions of transportation NO_x emissions savings across all scenarios (Fig. 7). The additional demands within the light-duty vehicle sector prompt changes in investment patterns in heavy-duty and other modes to meet the CO_2 constraints. We observe more fuel-efficient heavy-duty vehicles and buses in earlier periods relative to REVOLUTION and DEPENDENCE (Supplementary Fig. 10). By 2035, both TNC scenarios phase out diesel-fuelled buses and convert the fleet to CNG and electricity. The use of CNG in heavy-duty short-haul vehicles becomes even more prevalent compared to the DEPENDENCE scenario (Supplementary Note 4 provides in-depth results).

The MODESWITCH scenarios investigate behavioural changes in transportation mode choices (for example, reduced light-duty demand through a switch to walking, biking or increased use of public transit; Supplementary Note 5). DEP_MODESWITCH and REV_MODESWITCH model higher trip shares in public transit and light-duty demand

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reductions due to increased walking and biking. We observe a 7% further reduction in fuel consumption per passenger mile of travel on subway and buses in DEP_MODESWITCH relative to REV_MODESWITCH in 2050. Interestingly, for the period from 2010 through 2050, the aggregate fuel consumption results are slightly more than in the DEPENDENCE (1.7%) and REVOLUTION (0.7%) counterparts. When we reduce light-duty vehicle demands in the MODESWITCH scenarios, heavy reductions in fuel consumption to yield CO_2 benefits are no longer needed. Increased walking, biking and public transportation relax the need for intensive CO_2 mitigation. Therefore, the model meets the 80 × 50 target at a much lower discounted total system cost through investing in cheaper and less-efficient vehicles. This strategy, in turn, raises the average fuel consumption per passenger mile. In REV_MODESWITCH the penetration of electric cars is still limited in the early period of the projection period compared to the DEP_MODESWITCH scenario. The undiscounted total system cost is lowest for these walking, biking and transit-oriented scenarios due to reduced need for aggressive turnover investments in the light-duty vehicle fleet as discussed further in Supplementary Note 6.

Discussion and conclusions

Understanding the transportation-related energy and air emissions implications of NYC's CO_2 reduction policies in the context of the full energy system, while considering uncertainty in the pace of electric grid decarbonization, contributes to the sustainability of transportation energy transitions. Here, we were able to quantify the transportation-related air pollutant emissions co-effects of CO_2 reduction targets by leveraging an energy system approach. We captured detailed technology and fuel switching dynamics in transportation sub-sectors and provided insights for policy-specific actions for public transit modes and the heavy-duty sector.

The city-level modelling captures greater shares of public transit energy use than what is typically found in national or global energy system models. This enabled assessment of fuel switching effects across transportation modes, driven by two bounding scenarios for electric sector CO_2 intensity (DEPENDENCE and REVOLUTION). For example, DEPENDENCE sees a higher level of fuel switching across multiple modes, both for passenger and freight. Fuel switching from diesel to CNG in modes such as transit buses and short-haul freight modes would not have made a pronounced impact using a national-level model, or even state-level model in the United States. At the city scale, however, this switching results in deeper reductions in NO_x and PM_{10} emissions. Specifically, the deepest transportation air emissions reductions are in the DEPENDENCE scenario and its variants. Overall, the main reason DEPENDENCE scenarios resulted in more cumulative reductions in the transportation sector is because the carbon budget allocated in DEPENDENCE for end-use sectors is much smaller compared to REVOLUTION scenarios due to the higher electric sector CO_2 emission rate.

The timing of the fuel and technology switching is also important for emissions reductions. The REVOLUTION scenario postpones fuel efficiency improvements in the near term and invests in battery electric vehicles more heavily in later years. The model finds that investing early in fuel-efficient and electric vehicle technologies results in the most cost-effective

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strategy for DEPENDENCE to reduce total CO_2 emissions. This vehicle electrification strategy may sound counterintuitive when the electricity grid emissions are higher. However, from a systems-level perspective, considering perfect foresight, because deeper emissions reductions would be needed from transportation, early light-duty electrification is a strategy with air emissions co-benefits. The discounted total energy system cost for NYC for DEPENDENCE is lower than that of the REVOLUTION scenario. Here, the value of early action in investing in technology and fuel efficiency can be observed through resultant multiple co-benefits ranging from air emissions reductions through investment cost reductions. The vehicle electrification also results in NO_x and PM_{10} emissions reductions. The substantial NO_x and PM_{10} emissions reductions in the transportation sector will also have public health benefits given the proximity to exposure of major population areas.

A city-level version of an energy system model is also insightful when more broadly considering the role of electricity in transportation. A noteworthy portion of the literature focuses on increased load to the electric grid when light-duty electrification occurs. NYC and likely other large urban areas are special cases as the majority of the electricity consumption that belongs to transportation sector is already happening through subways and commuter rail (94% of transportation sector electricity consumption). For that reason, it is also important to consider impacts of further efficiency improvements in already electrified subway and rail transportation. The push for light-duty electrification in the BATTERY scenarios did not greatly increase the overall grid demand from the full transportation sector when considering the existing load from the subway system. One should note that depending on the time of day, the seemingly minor increase in vehicle charging might trigger demand increase during peak demand times and consequently increase use of peak-load units within the grid as well as use of inefficient but cheap fossil-fuelled distributed energy resources[29].

This work demonstrates the influence of technology and fuels on how cities could achieve their CO_2 reduction targets. There are, however, uncertainties in how people and goods will move in the future. To further evaluate the robustness of our insights, scenarios of mode switching to walking, biking and transit (MODESWITCH) assume reductions in light-duty vehicle demands. MODESWITCH scenarios show that if the city can reduce the demand for light-duty vehicles, the need to invest in fuel efficiency is reduced. Modelling other scenarios of increased ride-hailing and use of TNCs, the model cost-effectively offsets the CO_2 impact of increased light-duty vehicle mileage through deeper fuel switching in heavy-duty short-haul vehicles and buses.

The discounted total system cost of the scenarios average 1.2 to 1.4 times the cost of STEADY-STATE, and the discounted demand technology investment cost, including building and transportation demand technology investments in the city, range from 1.2 to 1.5 times the investments occurring in STEADY-STATE (Supplementary Table 6). Considering NYC alone, all DEPENDENCE and REVOLUTION scenario pairs resulted in a two to seven percent deviation from each other. The main driver of this deviation is found to be the demand level. Hence, the maximum difference between the REVOLUTION and DEPENDENCE counterparts is observed under the scenario with higher light-duty vehicle demand (TNC).

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The CO_2 reduction goal, regardless of sector, will drive up the technology investment costs. However, along with cumulative CO_2 reductions, noticeable savings in emissions of NO_x, PM_{10} and other pollutants can be achieved. We observe that both transportation-related and system-level NO_x emissions decrease, for scenarios such as DEPENDENCE, where the CO_2 intensity of electricity was relatively higher than the planned trends assumed for the 80 × 50 policy (Supplementary Fig. 4). We also observe a decrease in emissions in the buildings sector (Supplementary Figs. 1 and 3 for a brief discussion). The buildings sector is more sensitive to the emissions intensity and price of electricity in CO_2 reduction scenarios. Buildings rely heavily on electricity, and all the end-use service demands in the buildings can be electrified more easily. Therefore, the buildings and electric sectors are coupled more tightly than the transportation and electric sectors. Hence, we observe a lower investment cost for the technologies meeting building sector energy demand than the ones for transportation. Moreover, REVOLUTION scenarios result in less building end-use technology investment cost than DEPENDENCE scenarios. The push for decarbonization of the electricity grid in REVOLUTION results in higher costs in the electric sector; however, we observed lower investment costs in the city's buildings sector. Supplementary Note 6 delves into a detailed cost discussion.

Overall, the electric sector CO_2 rates influence the resultant technology, fuel choice and air emissions across the scenarios. Here, we find that early electrification of light-duty vehicles and the bus fleet, fast turnover to more efficient light-duty vehicles and subway cars, and switching to low-carbon intensity fuels such as CNG in the heavy-duty sector are part of a robust system-level CO_2 mitigation strategy given the uncertainty of the electric sector CO_2 intensity. Most cities will have policy levers to transform the mode share and resulting energy demand, incentivize energy-efficient technology investments and implement fuel switching in the public transit and municipal service fleets. No matter how the electric grid evolves, our analysis found that focusing on public transportation and the heavy-duty fleet will result in hedging against future uncertainties in the electric grid. The most cost-effective way to reduce light-duty sector emissions is through demand reduction. However, the mechanisms that yield demand reduction may have external costs, which is beyond the scope of our study. Following demand reduction, efficiency improvements and electrification, even under scenarios with higher CO_2 intensity of electricity, yielded robust strategies to achieve emissions reduction goals.

Methods

COMET

This analysis uses COMET, developed by the US Environmental Protection Agency (EPA) and applied to NYC[19,30]. COMET fills the gap in facilitating urban-scale analysis of integrated strategies for energy planning that considers costs and emissions implications of technology pathways meeting energy demands as noted in Supplementary Note 8. COMET-NYC covers NYC's geographic boundaries with five administrative divisions (that is, boroughs) and also includes all electricity generation units located in New York State. The goal is to conduct scenario analysis incorporating the drivers of the change in demand and technological advancements under the set of variables including population growth, fuel

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supply and cost, and consumer choice, as reflected by technology-specific hurdle rates. The model is structured to capture changes in end-use demands in NYC at the five-borough level, but also accounts simultaneously for power sector changes at the state level.

COMET-NYC is built on MARKAL optimization framework[19]. MARKAL identifies the cheapest technology pathway in the energy system, meeting predefined end-use energy service demands, and primary energy resource quantities and prices defined for a region. Loulou et al.[30] present the mathematical formulation of the MARKAL framework. Researchers from academia, non-governmental organizations and federal research laboratories have applied and used the MARKAL model for applications ranging from system-wide policy analysis to specific technology evaluations[29,31,32,33,34,35,36]. A MARKAL model includes four main components: (1) The component of demand incorporates end-use energy service demands for the residential, commercial, industrial and transportation sectors. These demands can be, for example, vehicle miles of travel, lumens of lighting or square foot of space heating. The demand drivers, such as gross domestic product, population and number of family units, are obtained externally either from city-specific sources or by relying on projections from the Energy Information Administration's Annual Energy Outlook1. (2) The component of supply describes the cost and quantity relationship for the extraction and processing of primary energy resources such as coal, natural gas, crude oil, biomass feedstocks and other non-biomass renewable resources. (3) The component of policy incorporates energy and environmental policies, standards and regulations. (4) The techno-economic component characterizes energy conversion (for example, electricity generating units and refineries) and demand (for example, light-duty vehicles and furnaces for space heating) technologies. All technologies are specified by capital investment and operation and maintenance costs, performance characteristics (capacity, fuel efficiency, availability) and emission factors. Throughout the model, we include emission factors for CO_2, NO_x, CH_4, SO_2, PM_{10}, $PM_{2.5}$ and mercury associated with the extraction, processing, conveyance and conversion of primary energy resources to fuels and electricity and the combustion of fuels.

MARKAL then solves for the lowest system-wide cost (that is, total discounted investment, operation and maintenance, and fuel costs per technology), with the optimal mix of energy technologies and fuels, while satisfying energy balance constraints and end-use service demands and meeting constraints on policies and regulatory standards such as air quality regulations and vehicle efficiency standards. For instance, the electricity use per demand technology is not prescribed to the model. The model decides how much of the end-use service demand is met by electric powered end-use demand technologies. Per each demand, COMET calculates a levelized cost accounting for fuels and technology. The model calculates the resultant electricity and fuel marginal costs endogenously for all years. Based on annualized discounted costs, the model calculates the absolute electricity and fuel demands per sector (that is, transportation and buildings) per modelling period, then determines the least-cost capacity expansion pathway in the electric sector to meet the end-use service demand. Supplementary Note 8 and Kaplan and Isik[19] provide additional detail on the model.

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Power sector assumptions and inputs—COMET-NYC represents all the utility-scale electricity generation units in New York State including peaking fossil-fuel-based generators. In addition, the model includes representation for distributed energy resources such as roof-top solar photovoltaic, and combined heat and power within New York City. We utilized generator-level power sector data collected and published (Form EIA-860) by US Department of Energy which reports operational electric sector capacity in 2010 and 2015 (ref. 37). There are 115 distinct electric generating units in New York State, which generated 493 PJ (~136 TW h) electricity in 2010 (ref. 19).

Transportation sector assumptions and inputs—Five distinct transportation modes were modelled in COMET-NYC, namely, light-duty vehicles, heavy-duty short-haul vehicles (for example, garbage trucks), medium-duty short-haul vehicles (for example, commercial trucks), buses and public rail transit (for example, subway). COMET-NYC captures in-city transportation demands and related technologies to meet this demand including existing fleet characteristics, average 2010 fuel efficiency for each transport mode and feasible future technology options. Light-duty vehicles are represented through seven vehicle class sizes: mini-compact, compact, full size, minivan, pick-up truck, small sport utility vehicle and large sport utility vehicle. Each class size is modelled through available technology options distinguished by fuel types and efficiency levels (Supplementary Table 7 for light-duty vehicle technologies, and Supplementary Table 8 for heavy-duty and other transportation mode technologies).

Other transportation categories include bus, medium- and heavy-duty trucks and passenger rail subcategories. Our analysis focuses on heavy-duty short-haul trucks. The reported fuel consumption data provided by NYC does not have the split between short-haul and long-haul trucks. Hence, it is assumed that all reported fuel consumption belongs to heavy-duty short-haul trucks.

New subway cars (for example, R211) are expected to be in service between 2020 and 2025. In 2020, partial efficiency gains are modelled, and full efficiency gains are assumed to start in 2025, representing the rollout of the more efficient cars. The benchmark efficiency improvement rate is taken from the American Public Transportation Association statistic[38].

COMET is an optimization model based on linear programming. It reaches optimal value by finding the best candidate in the feasible region shaped by the constraints. Constraints are used to adjust the feasible region by considering the real-world limitations. User-defined constraints do the following: calibrate the fuel shares and consumption in the transportation sector as reported in the 2010 New York City Greenhouse Gas Inventory Report and Annual Energy Outlook historical data up to 2010; limit maximum market penetration for 100-mile and 200-mile battery electric vehicles, fuel cell vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, advanced internal combustion engine vehicles meeting the demand for light-duty vehicles and CNG vehicles meeting the demand for heavy-duty vehicles; calibrate the distribution among car classes; and increase the energy efficiency by 2.4% per time period until 2030 to meet the EPA's National Corporate Average Fuel Economy standards in the light-duty sector. One may view these constraints prescribing the results; however, many of them are necessary for the least-cost optimization model to calibrate the

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results. Supplementary Note 9 delves into the role of constraints and how it influences the results.

Where NYC-specific data is unavailable, we rely on Census-Division-level data from the Energy Information Administration and US EPA's Regional MARKAL model (EPAUS9r)[39]. NYC is located in the Middle Atlantic Census Division (covering New Jersey, New York and Pennsylvania). The demand for light-duty vehicles is projected to increase in line with the national vehicle miles travelled reported in the Annual Energy Outlook 2016 (ref. 1) for this region.

Annual Energy Outlook 2016 (ref. 1) forecasts fuel consumption shares with respect to the fuel types for each end-use demand sector until year 2040. The fuel shares (for example, fraction of gasoline meeting the demand for light-duty vehicles) are kept identical to those for the calibration years (2010 and 2015). For the modelling years (2015–2040), the fuel share forecasts are implemented as lower bounds. Beyond 2040, the fuel share forecasts for 2040 are relaxed per each modelling period to provide flexibility to switch to different types of vehicle technologies and fuel types to meet travel demand.

Transportation sector emission factors for each vehicle type and fuel are gathered from the US EPA's Motor Vehicle Emission Simulator (MOVES)[40,41]. MOVES creates emission factors for on-road motor vehicles and gathers estimates of emissions from cars and trucks under a wide range of user-defined conditions, for example, vehicle types, time periods, geographical areas, pollutants and vehicle operating characteristics. Due to the unavailability of New York State county-specific driving cycle data, we ran MOVES at the regional level to generate emission factors, which are also used in EPAUS9r (ref. 39). Supplementary Note 10 provides discussion on the validity of using regional emission factors for NO_x.

COMET-NYC tracks fuel-combustion-related emissions as well as some process and leakage emissions occurring along the energy system. For instance, CO_2 emissions are tracked through quantity of fuel combusted and verified for 2010 and 2015 using NYC's Greenhouse Gas Inventory12. Methane emissions are tracked throughout the system, with the main contribution coming from oil and gas operations, which are beyond the geographical scope of this analysis. Criteria air emission factors are derived from US EPA's National Emissions Inventory platform[42].

A time frame from 2010 to 2050 is adopted for analysis. The calibrated model that is run reflecting business-as-usual conditions is called the STEADY-STATE scenario; a detailed discussion on results is given in Supplementary Note 1.

Buildings sector assumptions and inputs—COMET-NYC characterizes existing building stock through its end-use energy service demand and includes a suite of future technologies to meet these demands. This sector is built using the data collected under Primary Land Use Tax Lot Output files[43] and the NYC Benchmarking Law (LL84). The Primary Land Use Tax Lot Output files contain data on all buildings in NYC, where each building has a unique Borough–Block–Lot number. LL84 provides annual measurements of energy and water consumption[44]. Both pieces of data are matched (by Borough–Block–

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Lot number as well as reporting year) to allocate existing building stock to the associated energy use for each building. Buildings sector energy consumption is then allocated into end-use energy service demands (that is, space heating, water heating, space cooling, lighting, conveyance, process loads and miscellaneous). Data are utilized for city-wide site energy consumption levels by fuel type for different building types (multi-family, commercial, industrial and institutional) under major end-use energy service demands from the NYC Department of Health and Mental Hygiene to allocate the end-use demands. The energy consumption values must be paired with existing technology stock. Since there are no specific data for NYC, we rely on the US Energy Information Administration's Commercial and Residential Energy Consumption Surveys (CBECS and RECS). The technology capacity, costs and efficiency data for the Middle Atlantic Census Division is gathered for our calculations. Similarly, future technology representations are gathered from the Energy Information Administration and data in the EPAUS9r (ref. 39). Additional details on the buildings sector are given in Kaplan and Isik[19].

Scenario design—In the *Roadmap to 80 × 50*, the goal is to reduce CO_2 emissions by 80% by 2050, from 2005 levels of 59.2 $MtCO_2$. In addition to transportation sector goals, the buildings sector is to reduce CO_2 emissions by 45% from 2005 levels by 2030 and attain 80% reduction by 2050 (refs. 14,20,21).

The STEADY-STATE scenario illustrates a business-as-usual capacity expansion of the electricity grid encompassing the whole of New York State including in-city generation and the resulting emissions over the next decades. The end-use energy service demands and other inputs to COMET-NYC are based on internally consistent assumptions on population and economic growth. Model documentation15 includes details on demand calculations, and Supplementary Table 9 presents the transportation vehicle miles travelled demand time series assumed for the scenario analysis. Major implemented federal- and state-level air regulations that apply to the US energy system are modelled in the scenarios (Table 1). Fuel consumption and related emissions for the buildings, transportation and electric sectors are calibrated to the reported values for 2010 and 2015.

The overarching 80 × 50 target[14] is modelled through two separate constraints: one on buildings and another on transportation, which together attain a maximum of 16.5 $MtCO_2$ in 2050 in NYC (Supplementary Fig. 2). Each of these constraints will use the technology activity and its corresponding fuel consumption to calculate resultant CO_2 emissions. When a technology uses electricity as a fuel (for example, battery electric vehicles), the constraint assigns a CO_2 per kW h emission factor per period defined as input to account for the 80 × 50 target (Supplementary Table 10).

In DEPENDENCE, the upper bound constraint uses state-level electric sector CO_2 intensity coefficients that were observed in STEADY-STATE for each period. In REVOLUTION, the constraint uses the CO_2 intensity of electricity following the time series assumed in the 80 × 50 target. Furthermore, in REVOLUTION, another constraint satisfies the Clean Energy Standard. Both scenarios are free to decide to expand electric sector capacity based on cost considerations.

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Scenarios exploring electrification of light-duty vehicles—Given the uncertainties in the pace of vehicle electrification, we performed a sensitivity analysis on the level of light-duty electrification for both the DEPENDENCE and REVOLUTION scenarios (BATTERY variant). The percent of new zero-emission light-duty vehicle purchases in 2030 and 2050 for both DEPENDENCE and REVOLUTION scenarios are set to 15% and 50%, respectively. Our hypothesis is that this will be a primary driver in the reduction of CO_2 and criteria air pollutant emissions. Our analysis explores the net effects of light-duty electrification on not only fuel consumption and technology investment in the transportation sector, but also the whole energy system, given different levels of end-use electrification in other sectors and the rate of decarbonization of the electric sector. To analyse this hypothesis, we constructed four more scenarios in which new light-duty purchases in 2030 and 2050 increased by 25%, 50%, 75% and 100% relative to the baseline assumptions. Each level of zero-emission vehicles assumption is applied to both DEPENDENCE and REVOLUTION. For instance, DEP_BATTERY refers to a scenario where DEPENDENCE assumptions are applied, and all new zero-emission vehicle investment shares in 2030 and 2050 are now 30% and 100%, respectively. For the results and discussion, we will primarily focus on the 100% sensitivity runs as an upper bound. Supplementary Note 3 presents in-depth results, and Supplementary Table 11 presents demand levels.

Scenarios exploring use of TNCs—Recent increases in the ride-share mode of transport have been questioned by transportation planning authorities in terms of sustainability and impacts on light-duty demand and public transit[45]. The popularity of these for-hire vehicles, including those of Uber and Lyft, have amplified light-duty demand[46,47]. This situation causes a shift in the travel pattern, which is apparent in the data given in the New York City Mobility Report3. The mobility report also highlights that application-based hailing services have boosted for-hire vehicle trips by 90% since 2010 (ref. 3). As a secondary effect, this mode shift has reduced mass transit usage. Since 2013, subway and bus ridership have continued to decline despite the steady growth of the population. Moreover, with the increase of household vehicle registrations, light-duty trips have increased. To address the decline in public transportation usage, NYC puts new regulations and restrictions on the cruising cap and vehicle licences[48]. Additional sensitivity analysis was performed to analyse the impact of these trends on REVOLUTION and DEPENDENCE.

In this sensitivity analysis (TNC), subway and bus ridership values for the modelling years are kept at the 2015 value. The surplus public transportation demand for each modelling period with respect to values in the STEADY-STATE is added to light-duty demand using the assumptions below. Furthermore, the TNC scenarios set the share of walking and biking to 32.92% for the period between 2010 and 2050. New demands are calculated using the following assumptions: average number of passengers in a bus for NYC is set to 16.8 (ref. 49); average number of passengers in a car is set to 1.7 (ref. 49); average trip distance for walking and biking is set to 0.43 miles50; average trip distance for light-duty vehicles is set to 5.9 miles50; average trip distance for subway and commuter rail is set to 5.9 miles50; and average trip distance for bus is set to 5.9 miles50. Supplementary Note 4 delves into the TNC assumptions, and Supplementary Table 12 presents demand levels.

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Scenarios exploring transport mode changes

The city has taken steps (providing information via the Go Smart programme for local travel choices) to support walking, biking and public transit by opening new biking and pedestrian networks connecting to subway and bus services. This is an attempt to decrease the light-duty vehicle demand. To enable sustainable transportation futures and to achieve emissions reduction goals, the city plans to implement some policy actions that encourage and promote walking, biking and the use of public transportation. The target is to reach 80% of the sustainable mode trip share by 2050 (ref. 51). In this sensitivity analysis (MODESWITCH), light-duty vehicle demand is reduced by shifting 80% of the total number of trips to sustainable transportation modes for the period from 2020 to 2050. The new demands for respective transportation modes are calculated based on the following assumptions: average number of passengers in a bus for NYC is equal to 16.8 (ref. 49); average number of passengers in a car is equal to 1.7 (ref. 49); average trip distance for walking and biking is set to 0.43 miles50; average trip distance for light-duty vehicles is set to 5.9 miles50; average trip distance for subway and commuter rail is set to 5.9 miles50; and average trip distance for bus is set to 5.9 miles50. In addition, in 2015, we set the ratios for walking and biking, mass transit (bus, subway and commuter rail) and light-duty vehicle to 39%, 28% and 33%, respectively50; in 2050, the ratio for walking and biking, mass transit and light-duty vehicle is changed to 48%, 32%, and 20%, respectively50; and between 2015 and 2050, the ratios are interpolated linearly. Supplementary Note 5 delves into MODESWITCH assumptions, and Supplementary Table 13 presents demand levels.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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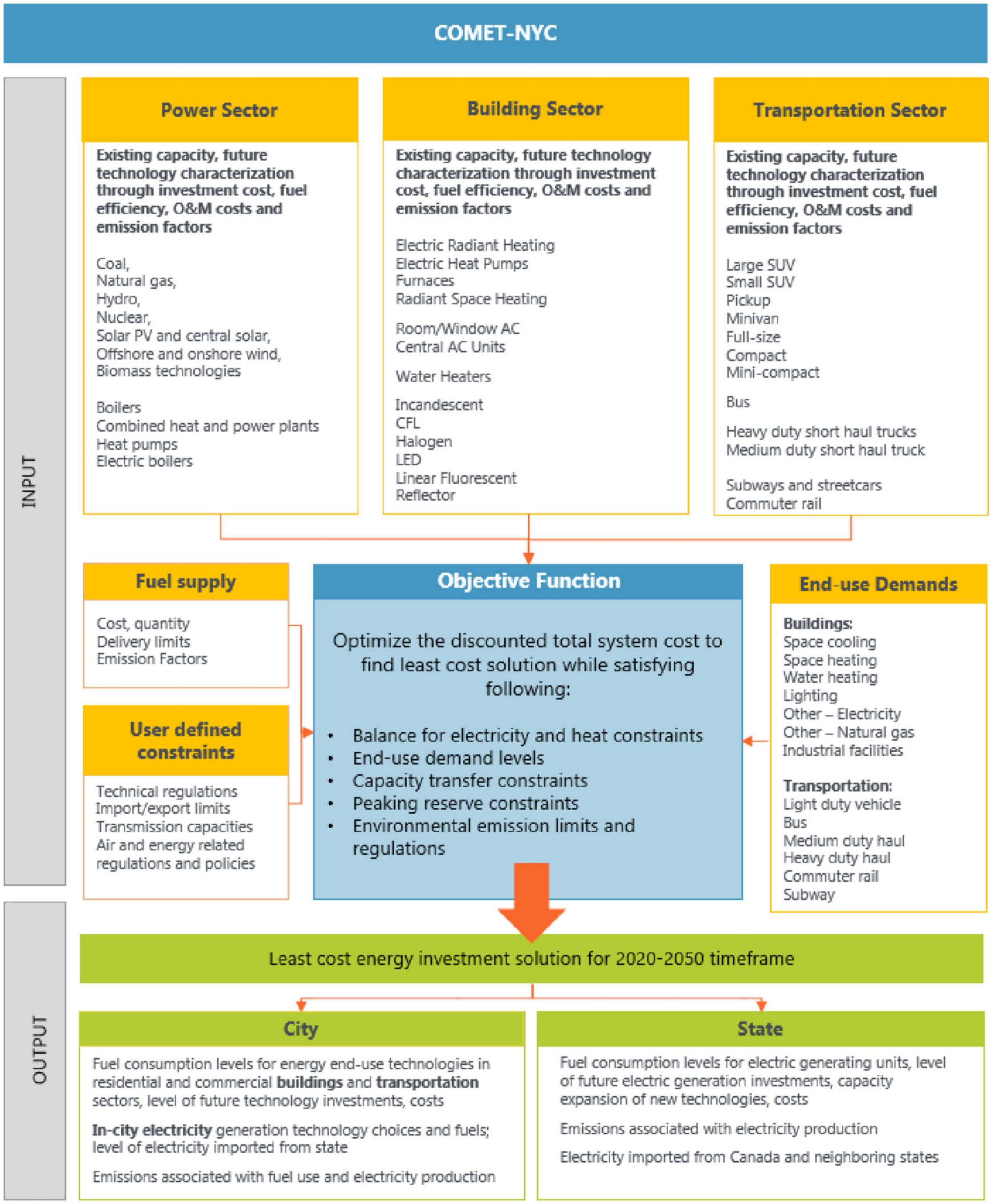

Figure 1. Figure 1 City-based Optimization Model for Energy Technologies: COMET-NYC structure.

This figure provides basic structural information about COMET-NYC. The objective function parameters are depicted in blue. Groups of constraints, model data requirements for each sector in the energy system and variables are presented in orange boxes where these parameters are the main inputs to the model. The outputs are listed in green boxes. The arrows show the information flow within the model.

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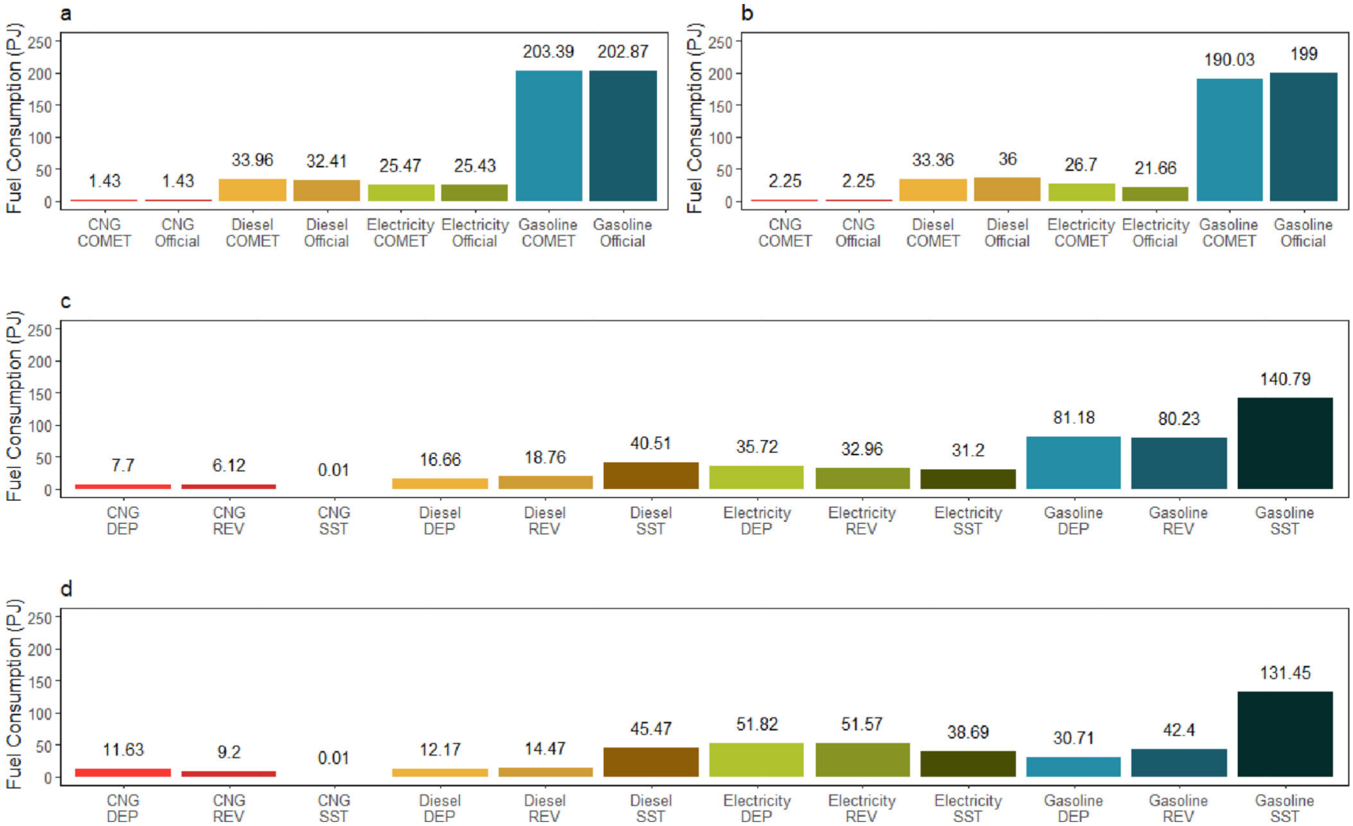

Fig. 2: Fuel consumption in PJ in transportation sector for STEADY-STATE (SST), DEPENDENCE (DEP) and REVOLUTON (REV)

Each chart represents a specific time in the modelling horizon: Panel (a) presents 2010, panel (b) represents 2015 modeling horizon. The vertical bar graph compares the fuel consumption reported by the city and model results that belong to transportation sector for the calibration years 2010 and 2015. (c) and (d) show the resultant transportation sector fuel consumption for STEADY-STATE, DEPENDENCE and REVOLUTION scenarios for 2030 and 2050. The color group represents the fuel type and each shade of the bar denotes the scenario type. See Supplementary Fig. 7 for city-wide electricity consumption, and transportation sector electricity consumption for all scenarios.

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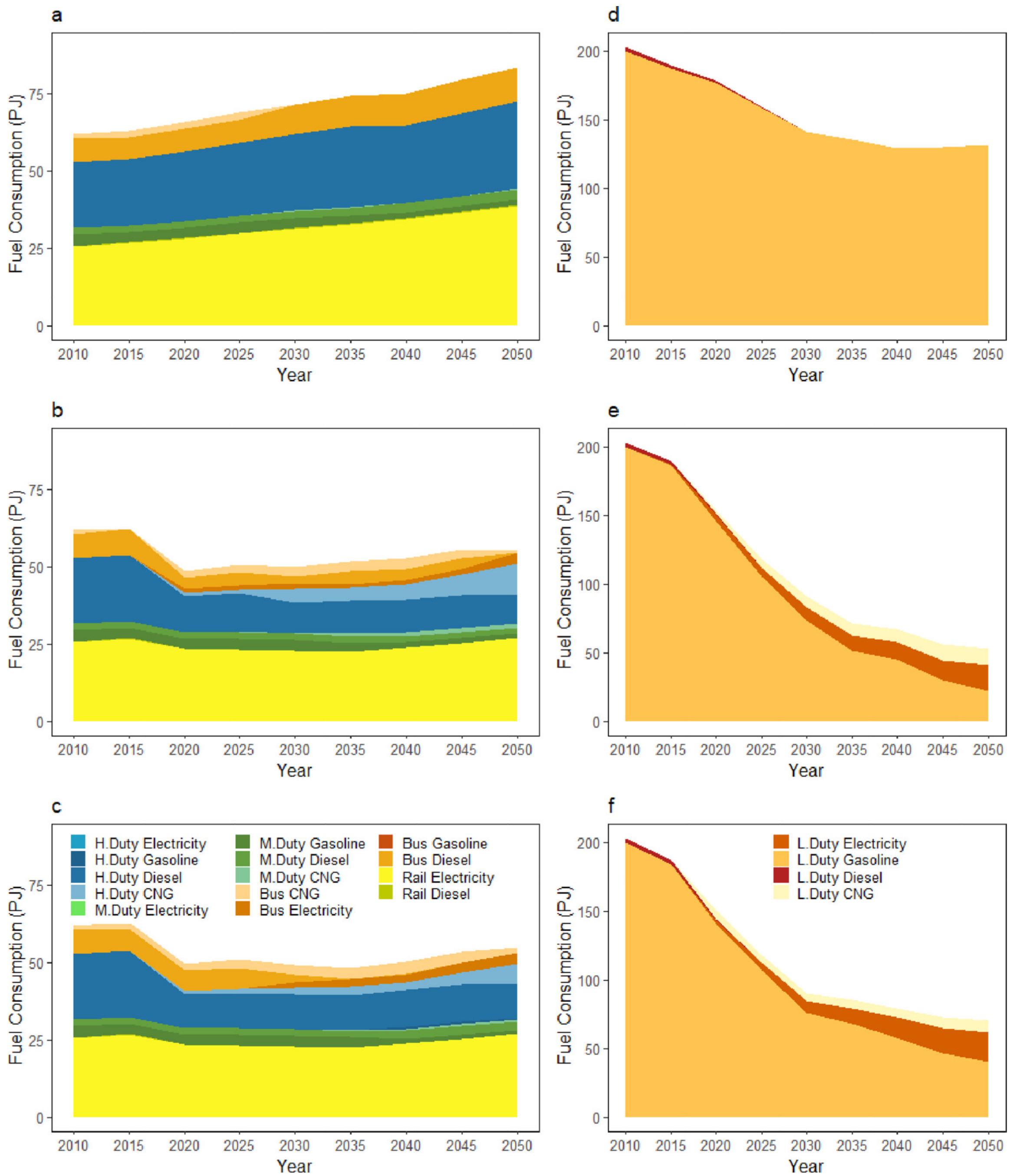

Fig. 3: Figure 3 Fuel consumption in PJ per mode of transportation in STEADY-STATE (SST), DEPENDENCE (DEP) and REVOLUTON (REV) scenarios.

The stacked area charts show the fuel consumption. Each color represents the type of the fuel. On the right-hand side, charts present the fuel usage that belong to the light-duty vehicles whereas the left-hand side charts present the change in fuel consumption values that can be attributed to heavy-duty vehicles from 2010 through 2050.

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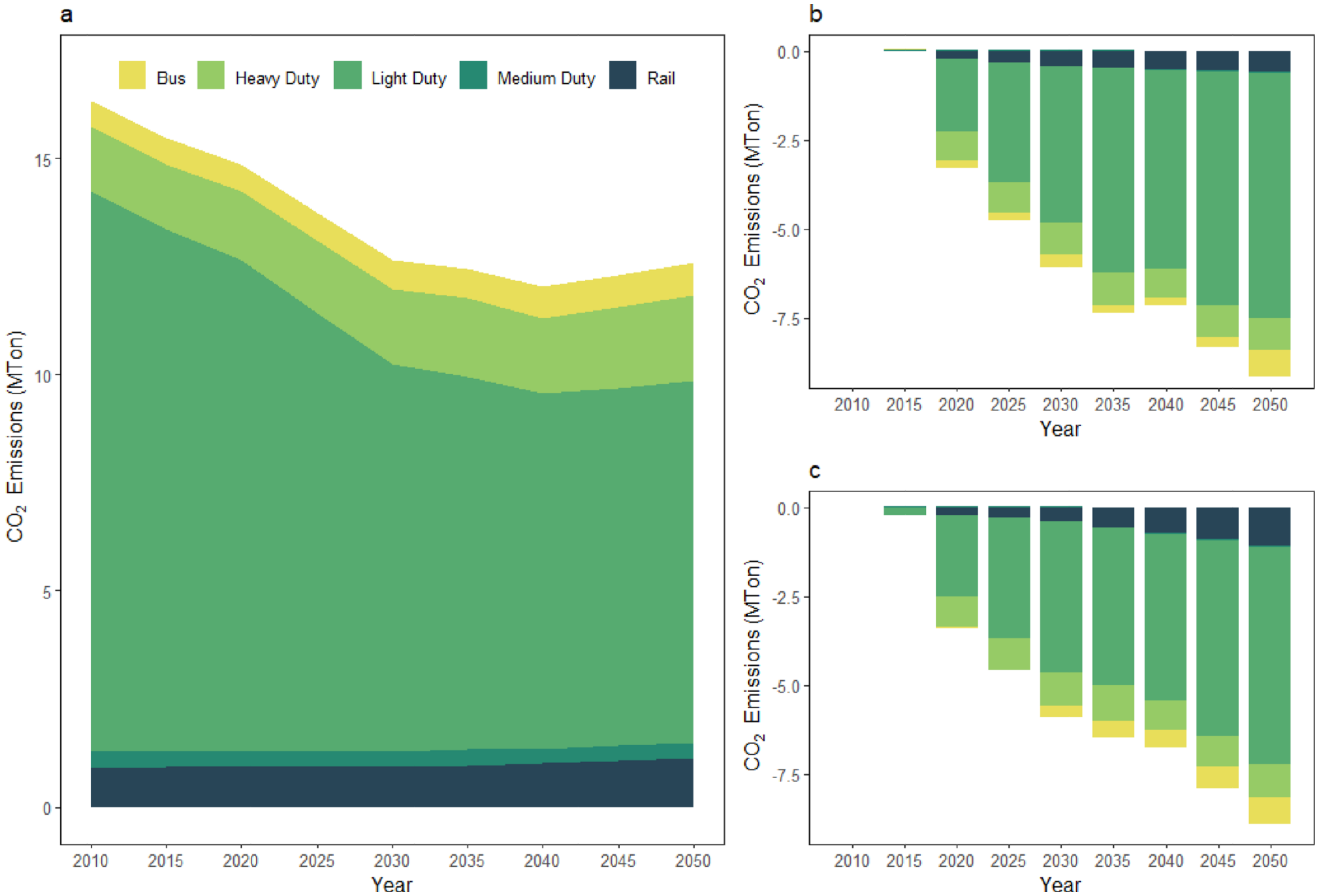

Fig. 4: Figure 4 Transportation CO_2 emissions in MTon in STEADY-STATE (SST), and emissions changes in DEPENDENCE (DEP) and REVOLUTON (REV) relative to STEADY-STATE.

The stacked area chart that belong to STEADY-STATE scenario shows the CO_2 emissions with respect to the mode of transportation. The downward growing stacked bar charts represent the emission reduction projections with respect to the STEADY-STATE scenario. For instance, DEP-SST is the difference between CO_2 emissions in DEPENDENCE and STEADY-STATE for each modeling year. See Supplementary Fig. 9 for results for sensitivity runs, i.e. BATTERY, TNC and MODESWITCH.

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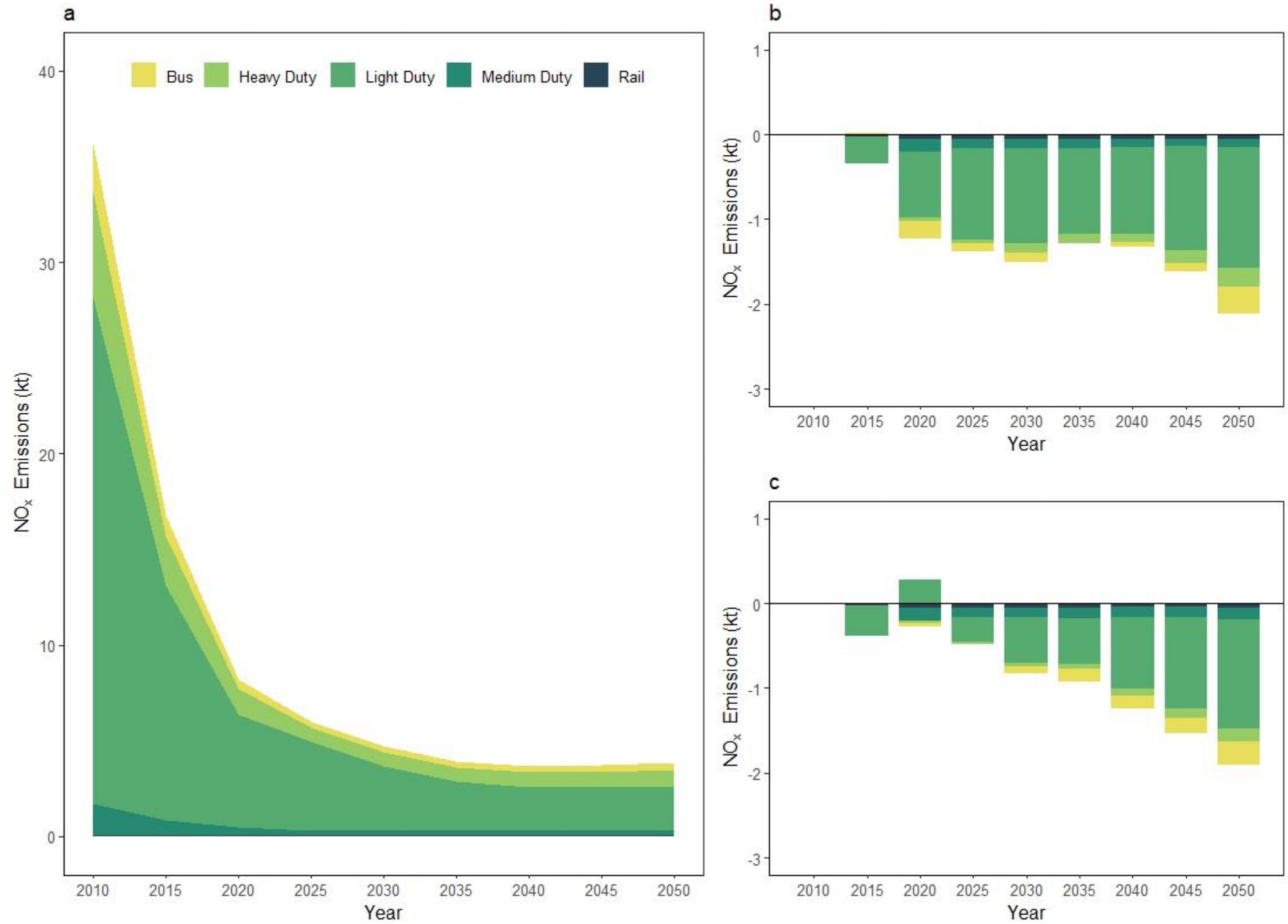

Fig. 5: Figure 5 Transportation sector NO_x emissions in kt in STEADY-STATE (SST), and emission changes in DEPENDENCE (DEP) and REVOLUTON (REV) relative to STEADY-STATE (SST).

The stacked area chart that belong to STEADY-STATE scenario represents the NOx emissions with respect to the mode of transportation. The stacked bar graphs show how emission mitigation scenarios result in NO_x emission benefits comparing to STEADY-STATE scenario. The downward growing stacked bar charts represent the emission reduction projections with respect to the STEADY-STATE scenario. For instance, DEP-SST is the difference between NO_x emissions in DEPENDENCE and STEADY-STATE for each modeling year.

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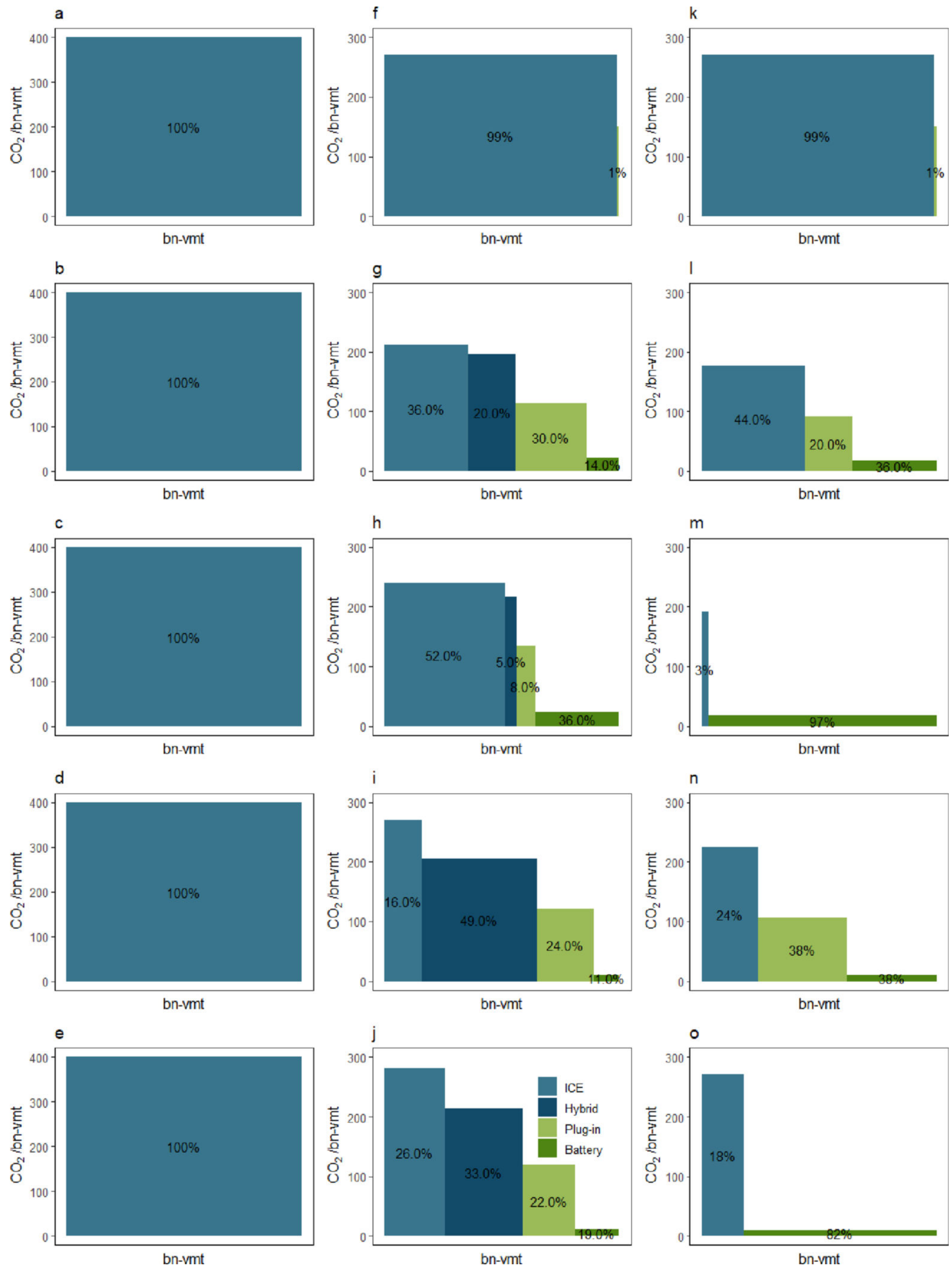

Fig. 6: Figure 6 Comparison of unit CO_2 emission rate for light-duty vehicle types.
Variable width column chart represents the change in the CO_2 emission values per vehicle miles travelled and total miles travelled (normalized) for light-duty vehicles regarding engine types in 2010, 2030 and 2050 for each of the scenarios: STEADY-STATE, DEPENDENCE and REVOLUTION. Each color represents the type of vehicle including internal combustion engine (ICE) and electric vehicles (Hybrid, Plug-in hybrid and Battery) whereas the column widths are scaled with respect to the share of the demand met by the vehicle type. The numbers within the boxes also represent shares as percentage.

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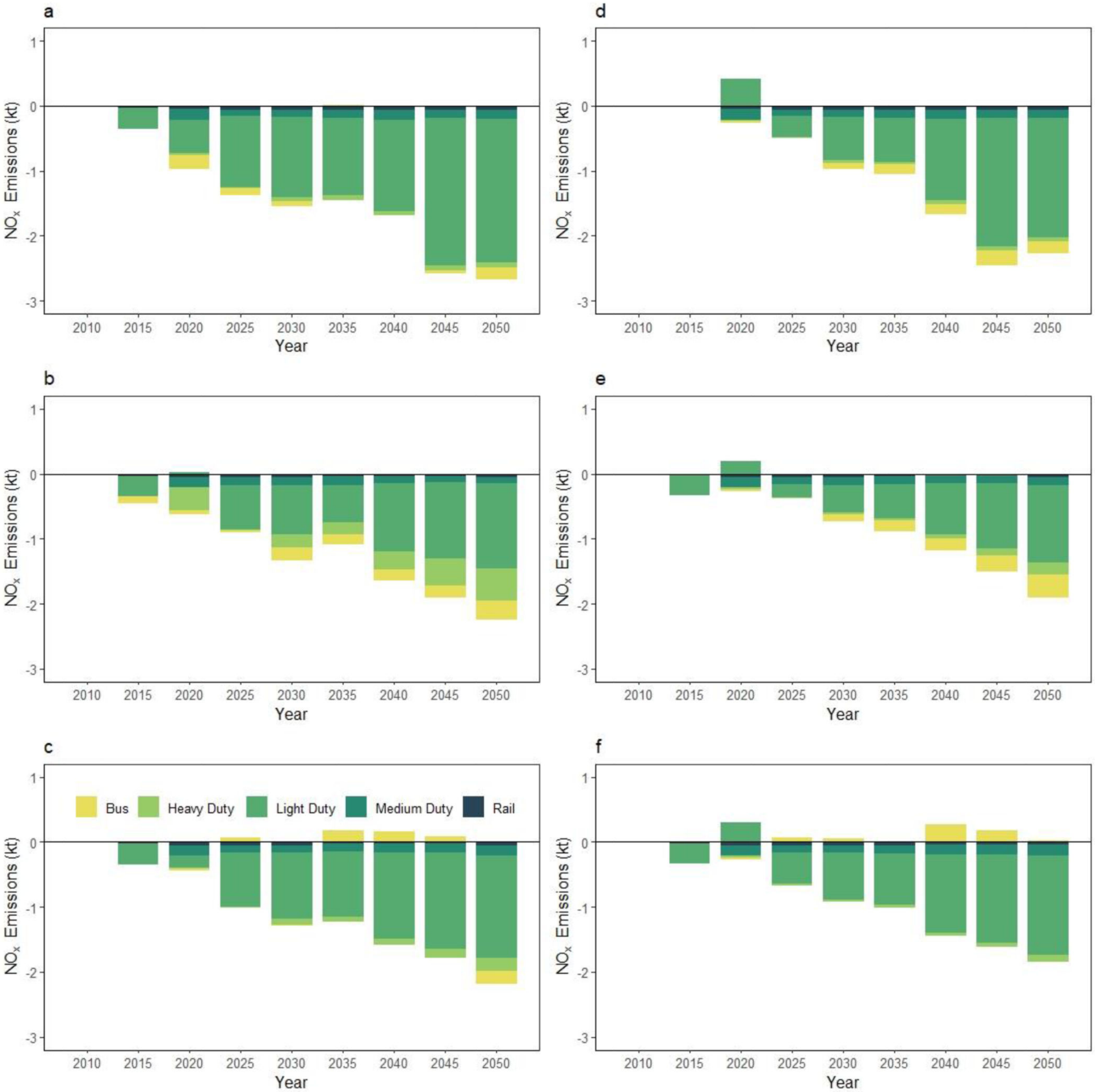

Fig. 7: Figure 7 Transportation NO_x emissions changes in BATTERY, TNC, MODESWITCH variation of DEPENDENCE and REVOLUTION scenarios relative to STEADY-STATE in kt.

The downward growing stacked bar charts represent the emission reduction projections with respect to the base case scenario. For instance, DEP_MODESWITCH-STEADY-STATE is the difference between NO_x emissions in DEP_MODESWITCH and STEADY-STATE for each modeling year.

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Table 1

Scenario descriptions and model assumptions for each sector

	STEADY-STATE: business-as-usual trends	**DEPENDENCE: slow decarbonization of the electric grid**	**REVOLUTION: fast-paced decarbonization of the electric grid**
Objective	To model current trends in energy consumption and technology turnover in buildings and transportation within the city.	To analyse in-city technology investments in end-use sectors to achieve a total of 80% emissions reduction by 2050 in NYC, where New York State fails to achieve CO_2 per kW h reduction.	To analyse in-city technology investments in end-use sectors to achieve a total 80% emissions reduction by 2050 in NYC, while New York State reduces CO_2 per kW h in line with clean energy standards.
Emissions	Existing federal air regulations applied, such as Corporate Average Fuel Economy, the US National Ambient Air Quality Standards, New Source Performance Standards and Tier 3 standards on motor vehicle emissions. There is no greenhouse gas emissions reduction policy.	All air regulations applied in STEADY-STATE are included. Buildings sector target (45% CO_2 emissions reduction from 2005 levels by 2030 and 80% by 2050) and transportation sector target (58% CO_2 emissions reduction from 2005 levels by 2030 and 82% by 2050) are introduced into the model.	Air regulations applied in STEADY-STATE are included. Buildings sector and transportation sector emissions reduction targets in DEPENDENCE scenario are included. Power sector target (40% CO_2 emissions reduction from 1990 levels by 2030, and 80% by 2050 in New York State's electric grid) is introduced into the model.
Power sector	Currently permitted and near-future planned coal, natural gas, nuclear and hydro power plants are added to the modelled capacity. Existing nuclear power plant capacity is kept operational throughout the modelling horizon. Electric sector capacity expansion is based on least-cost optimization of suite of technologies, which are available in the COMET-NYC database. We rely on Department of Energy, National Renewable Energy Laboratory, US Energy Information Administration and New York State Energy Research and Development Authority sources for future technology characterizations. All operational and in-progress solar capacity listed in City Solar is added52.	Electric sector assumptions in the STEADY-STATE scenario are included. A CO_2 constraint is not modelled for the electric sector; however, unit electricity intensity coefficients for end-use demand technologies are included to feed into the 80 × 50 target constraints (Supplementary Table 10). The capacity expansion decision is based on a least-cost solution.	Electric sector assumptions in the STEADY-STATE scenario are included. New York State Clean Energy Standard is included, which mandates 50% of electric generation from renewables by 2030. CO_2 emissions rate for electricity reported for New York State's Reforming the Energy Vision goals (40% reduction from 1990 levels by 2030 and 80% by 2050) is used for electricity consumed by the city (Supplementary Table 10). A constraint for solar photovoltaic capacity expansion ensures the invested capacity level is greater than or equal to 250 MW by 2025 (ref. 14). A constraint for renewable energy capacity expansion ensures the installed capacity is at least 3.6 GW by 2020 (ref. 53).
Transportation sector	STEADY-STATE assumptions on penetration of vehicle type, fuel and efficiency rates are applied. General assumptions are based on vehicle turnover and efficiency gains reported for the Middle Atlantic Census Division in Annual Energy Outlook 2016.	Assumptions for existing vehicle stock introduced in STEADY-STATE are included. Zero-emission vehicles are projected to compose 15% of new car purchases in 2030 and will be roughly half of all new cars sold in 2050.	Transportation sector in REVOLUTION scenario has the same technology assumptions valid for DEPENDENCE scenario. The difference between the DEPENDENCE and REVOLUTION scenarios is the emission coefficient of the unit electricity consumed by the transportation sector. Supplementary Table 10 presents unit electricity coefficients.
Buildings sector	Buildings sector includes the representation of existing building technology stock and is calibrated to actual reported energy consumption. Future energy demand forecast uses population projections and assumptions on the change in the floorspace reported for the Middle Atlantic Census Division in Annual Energy Outlook 2016. Annual Energy Outlook reports data at nine census divisions, and New York is in the Middle Atlantic Census Division. Equipment efficiency improvements and fuel shares reported in the Middle Atlantic Census Division of Annual Energy Outlook 2016 are incorporated into the model as lower bounds for future technology investments.	Assumption for existing building stock and technology characterization is the same as in the STEADY-STATE scenario. The future technology mix deviates greatly from STEADY-STATE due to faster technology turnover and fuel switching.	Buildings sector in the REVOLUTION scenario has the same technology assumptions valid for the DEPENDENCE scenario. The difference between the DEPENDENCE and REVOLUTION scenarios is the emission coefficient of the unit electricity consumed by the buildings sector. Supplementary Table 10 presents unit electricity coefficients.

Table 1 explains the objective and sectoral assumptions for each scenario. The first column presents the components of the model including objectives, sectors and representation of emission reduction policies, whereas each additional column contains a different scenario.

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