

Analyzing the Transportation and Climate Initiative Program Using an Integrated Assessment Model

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Abstract

The Transportation & Climate Initiative (TCI) is a cap-and-invest program that is designed to help the thirteen participating states reduce CO₂ emissions; however, the anticipated electrification of the transportation sector can potentially interact with the Regional Greenhouse Gas Initiative (RGGI) market, a cap-and-trade system for CO₂ emissions from electricity generation. Potential impacts include an increase in electricity prices and leakage of CO₂ emissions to other sectors and states. This study utilized a human-earth systems model to investigate TCI's regional emissions reduction potential and to quantify the impacts of the program under alternative assumptions. The results show that TCI would lower regional net CO₂ emissions and increase market penetration of both heavy- and light-duty electric vehicles through 2050. The emissions reduction and changes in transportation fuel mix would be accompanied by an increase in the RGGI CO₂ allowance price, as well as increases in the costs of electricity and on-road travel. In the freight sector, this resulted in a demand shift from trucks to trains and marine vessels. A portion of the CO₂ reduction from on-road transportation was offset by the increases in emissions from non-road transportation and electricity generation. Pennsylvania, the only TCI state that does not currently belong to RGGI, experienced the highest increase in CO₂ from the electric sector as well as the lowest percentage reduction of NO_x emissions, reflecting its own additional electricity demands and higher electricity exports to RGGI states. Extending the declining RGGI and TCI cap trends through 2050 leads to higher CO₂ and other air pollutant emissions reductions. In addition, it further facilitates the energy transition from carbon-based fuels to electricity in the on-road transportation sector. These results suggest that while TCI is effective at reducing regional CO₂ emissions, additional measures may be needed to avoid regressively burdening low-income households with the added costs. This is one of the goals of the TCI reinvestments, an aspect of the policy that was not modeled here.

Introduction

The Transportation and Climate Initiative (TCI) is a collaboration among twelve Northeastern and Mid-Atlantic states along with District of Columbia (D.C.). The goals of TCI are to facilitate a transition from fossil fuels to renewables in the transportation sector and to develop energy efficient transportation infrastructures in participating jurisdictions. In 2019, TCI proposed a regional cap-and-invest program for carbon dioxide (CO₂) emissions from on-road transportation across the participating jurisdictions¹. Eleven out of the thirteen potential TCI jurisdictions are also member states of the Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade program for power sector CO₂ emissions that was launched in 2009. RGGI and market changes have succeeded in driving a transition from coal to natural gas and renewables, resulting in reductions in that sector's regional CO₂ emissions. However, transportation has become the major source of CO₂ in the Northeast U.S., contributing over 40% of TCI regional total CO₂ in 2017². TCI has been designed to be a companion to RGGI, specifically seeking reductions of CO₂ emissions from on-road transportation. TCI is a voluntary program in which each member is expected but not required to participate in the cap.

To date, three states and the District of Columbia (D.C) have signed a Memorandum of Understanding that will result in a 4-state cap-and-invest TCI that starts in 2023. Additional jurisdictions are expected to adopt the TCI caps after policy makers refine the details of the regional program further. Nonetheless, these states currently are under no obligation to join the TCI program. Similarly, Pennsylvania and North Carolina have both expressed interest in joining RGGI but have not officially announced their decisions. Thus, there exist uncertainties in

¹ TCI's Regional Policy Design Process, 2020

² Transportation Sector Emissions, EPA, 2020

memberships of both the TCI and RGGI programs, how TCI will interact with RGGI, how the two programs can jointly affect regional carbon, electricity, and fuel markets, how TCI affect regional air pollution emissions, what will happen if the regulation periods are extended, if and where TCI has the potential to cause emissions leakage within the U.S, and how effective the program would be in a situation where not all TCI member states decide to join the program.

TCI is a relatively new program, and there are few studies that evaluate its performance. The Georgetown Climate Center modeling assessment of TCI which uses the National Energy Modeling System (NEMS), assumes that the reference case reflects an expectation of aggressive transportation policies in the near future³. Nevertheless, this study utilized a special version of the Global Change Analysis Model version 5.2 (GCAM v5.2) to investigate TCI's regional CO₂ emissions reduction potential, and possible impacts on regional transportation, electricity, and CO₂ markets. GCAM is of the class of integrated assessment models that takes a technology-rich approach to characterizing the interactions among the energy, economic, buildings, water, and climate sectors.

Background

The contribution of the transportation sector to the total CO₂ emissions of each TCI jurisdiction ranges from 29% in Pennsylvania to 55% in Maine⁴. The proposed TCI imposes annual, regional, emissions constraints on CO₂ emissions from gasoline and on-road diesel combustion. Emissions constraints are scheduled to become effective in 2023 and decline at a constant, annual rate that ensures a 26% reduction from on-road transportation from 2022 to 2032. TCI requires state fuel suppliers to purchase allowances for the CO₂ emissions caused by

³ The National Energy Modeling System: An Overview 2018, 2019

⁴ 2017 State energy-related carbon dioxide emissions by sector, 2020

the combustion of the fuel that they sell in participating jurisdictions. Excessive allowances will be auctioned to create revenue, which each state has the autonomy to determine how best to use in making equitable, low-carbon transportation investments⁵. Emissions reductions from on-road transportation is likely to incentivize electrification of the transportation sector, which can complicate the outcome through interactions with the RGGI market since it imposes a constraint on regional CO₂ emissions from electricity generation.

The latest TCI modeling analysis by GCC suggests that the potential 13-jurisdiction TCI program would reduce CO₂ emissions from on-road transportation in participating jurisdictions by 30% from 2023 to 2032, raising billions of dollars of economic growths, improving public health from reduction in air pollution, and creating billions of dollars for low-carbon transportation investments⁶. The study used a modified version of NEMS, TCI-NEMS, paired with the TCI Investment Strategy Tool. The TCI-NEMS, an integrated energy-economy modeling system designed for the United States, simulates the influence of the program on regional energy markets, while the Investment Strategy Tool was used to investigate the economic cost and benefits of the program⁷.

In the GCC analysis, the reference case represents a business-as-usual scenario where current transportation and energy policies along with RGGI are operating as-usual in absence of TCI. The reference case, however, also assumes that existing vehicle standards and reductions in electric vehicle costs would continue to improve as a result of the new federal administration's efforts to address climate change.

⁵ Framework for a Draft Regional Policy Proposal, 2019; TCI Modeling Summary, 2020

⁶ Estimating the Regional Environmental, Health, and Economic Benefit and Costs of the Transportation and Climate Initiative Program, 2020

⁷ Modeling Methods and Results from TCI Regional Policy Design Process, 2020

Under the baseline assumptions, their modeling suggested that regional on-road transportation CO₂ would decline by 24% by from 2023 to 2032, even without the TCI cap⁸. The modeled policy scenario consists of annual CO₂ emissions constraints on on-road CO₂ emissions in TCI jurisdictions, which declines linearly until 2032, and a selected investment portfolio that assumes how program revenue will be allocated to invest in a variety of transportation projects.

Alternatives to TCI-NEMS exist that can also be used to analyze TCI performance. For example, many Integrated Assessment Models (IAMs) also represent the transportation and electric sectors, and thus have the potential to capture the interactions between them. While most IAMs are too coarse spatially to represent dynamic state and regional policies, there are currently several that could be applied to analyze TCI. Furthermore, IAMs typically operate very differently than energy system optimization models, and thus may produce different insights. In many other applications, multi-model comparison analysis was used to assess policies. The differences in model structures, operation, and assumptions can result in different insights that together aid in the development of robust policies⁹. Considering that impacts of TCI have only been previously evaluated using the TCI-NEMS model, analysis with other models that use alternative formulations and assumptions could be beneficial. This study investigated TCI's regional emissions reduction potential and quantified its impacts under alternative assumptions and pathways using GCAM v5.2 – USA.

Literature Review

While TCI is still under development, it has been studied from multiple perspectives. As part of the latest modeling report, GCC also conducted sensitivity analysis on a number of TCI

⁸ See 6

⁹ Model comparison of mitigation strategies and costs, Edenhofer, et al, 2010

scenarios and investment portfolios. The results suggests that TCI would have small but positive effects on regional GDP, income, and employment. Furthermore, with the effect of potential investments funded by the program revenue, CO₂ allowances will start from around \$6.6/Mt CO₂ in 2023 to \$12.5/Mt CO₂ in 2032¹⁰. A preliminary analysis conducted by the Harvard University's Center for Climate, Equity, and Global Environment suggests that TCI will create significant health benefits from improved air quality and transportation infrastructures, reaching up to \$3 billion dollars in annual health and safety benefits in 2032. The study also reported that while health benefits occur in all communities, minority populations would still have a higher exposure to the negative health impacts of air pollution¹¹. Environmental justice and equity issues involving TCI have been brought to the attention of state-level decisionmakers, arguing that a carbon trading scheme would likely create pollution hot spots in minority communities and regressively impose a higher cost on transportation and energy¹².

Given the RGGI's targets have been specified only through 2030 and the TCI through 2032, existing studies have mainly focused on the policy's impacts in the next decade, whereas many national and global GHG emissions reduction targets specify horizons that stretch to midcentury or beyond. This is an aspect that is tackled here by creating an extended scenario, where the final targets for RGGI and TCI are extended through 2050. An alternative is also modeled in which the emission reduction trajectories of the policies are continued linearly into the future. Thus, in this alternative, the RGGI and TCI targets are more ambitious. Program targets will be discussed in more detail under Scenario Design. Note that while investing revenue from allowance actions has the potential to lower the mitigation costs of achieving emissions

¹⁰ See 6

¹¹ Harvard C-CHANGE, 2021

¹²Insider NJ, 2020

reduction goals set by the TCI cap and create co-benefits in other sectors, this paper focuses on the impacts of the emissions constraints alone. Analysis of the investment impacts is beyond the scope of this paper but could be addressed in subsequent research.

Methods and Model

GCAM-USA v5.2

This policy analysis utilized a modified version of the Global Change Analysis Model (GCAM). GCAM is a partial equilibrium, integrated human-earth systems model that links five human and natural systems, including energy, land use, water, economic, and climate. The model operates from 1990 to 2100 in 5-year increments, generating outputs for 32 geo-political regions and 384 land-water regions represented by GCAM¹³. Furthermore, GCAM is an input-driven model, meaning the inputs are generated based on both historical data and technological advancement parameters that can be modified to represent different policy scenario and assumptions about future market trends, such as technology advancement and costs¹⁴.

GCAM-USA v5.2 is a special version of GCAM that includes higher resolution state-level spatial detail in the U.S. GCAM-USA treats all 50 U.S. states plus the District of Columbia (D.C.) as individual regions operating within the global GCAM. GCAM-USA v5.2 includes U.S.-specific representations of technology cost assumptions, state-specific power plants retirement plans, and state and service-specific transportation demands. Overall demands for energy services are determined by the base demand and projected growth in GDP and population¹⁵.

In contrast to the TCI-NEMS model, which has the goal of minimizing the net present value of the cost associated with the energy system, GCAM-USA is a simulation model that

¹³ Calvin et al, 2019

¹⁴ Kim et al, 2006

¹⁵ Joint Global Change Research Institute. (n.d.)

steps through time myopically. In addition, TCI-NEMS achieves optimization by adopting attributes of future technologies in consideration of future policy targets. GCAM-USA, however, computes market share for competing technologies using a logit function which accounts for the cost and a share-weight parameter that characterizes historic trends and biases. Share-weights are calibrated based on historic technology market shares but are relaxed over time to grant the model more flexibility.

Calibration of GCAM v5.2 – USA

To isolate the role of electric vehicle in future markets, hydrogen-powered vehicles are assumed to be unavailable in the future. Similarly, we limit the market penetration of light-duty compressed natural gas (CNG) vehicles. While these vehicles achieved some market penetration earlier this century, there currently are very few on the road and there are no signs that their market shares will grow. The calibration also includes updated electric vehicle market share-weight and cost parity for both light- and heavy-duty vehicles, representing a market where electric vehicles become increasingly competitive with conventional vehicles, both in terms of an elimination of consumer bias (e.g., from range anxiety) and cost. The baseline assumption is that consumers are no longer biased against electric vehicles after 2035 for both heavy- and light-duty vehicles, and that EV capital costs reach cost parity with conventional vehicles by 2050.

RGGI and TCI are implemented in GCAM-USA by imposing constraints that cap annual electric sector and transportation sector CO₂ emissions, respectively. This implementation captures the big picture dynamics instituted by cap-and-trade programs but does not represent aspects such as the costs of managing the program or how permits are allocated. In addition, given GCAM's 5-year operation steps, TCI annual constraints decline from 2035 through 2035 (and 2050 for TCI-EXT). However, cap values applied in these two years are interpolated based

on reduction goals from 2023 through 2032. Similarly, values reported in this paper for years 2023 and 2032 are interpolated linearly from simulation output in 2020 and 2025, and 2030 and 2035.

The reference case includes several additional policies that influence GHG and air pollutant emissions. For example, a representation of the Corporate Average Fleet Efficiency (CAFE) regulation is included, forcing light duty vehicles to reach an efficiency standard of 52.5 miles per gallon by 2025¹⁶. In addition, a minimum EV market penetration scenario is included that forces light duty EV market penetration in line with the Section 177 ZEV targets¹⁷. The Cross-State Air Pollution Rule (CSAPR) is also represented by placing caps on emissions of nitrogen oxide (NO_x) and sulfur dioxides (SO₂) from the electric sector for many states in the eastern U.S¹⁸.

Scenario Design

In comparison to the GCC assumptions about more aggressive climate policies and technological development in the near future, this study is relatively more conservative about policy adoption and technological advancement. In general, our reference case involves policies that are “on the books”, as opposed to assuming that new policies will be adopted.

Policy Assumption	Baseline Scenario (includes RGGI)	Policy Scenario (BASE + TCI)
Hold sunset constraint through 2050	BASE	TCI
Continue linearly declining trend after sunset year	BASE-EXT	TCI-EXT

Table 1. Scenario Design

¹⁶ Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emissions Standards for Model Years 2022-2025, 2020

¹⁷ Zero-emission Vehicle Program, nd

¹⁸ Federal Implementation Plans: Interstate Transport of Fine Particulate Matter and Ozone and Correction of SIP Approvals, 2011

This study uses an experimental design that includes four scenarios, which can be grouped into two sets under alternative policy assumptions (Table 1). The first set of scenarios, BASE and TCI, assumes that both RGGI and TCI operate as designed through 2030 and 2032, respectively, and hold their final values through 2050¹⁹. Under this assumption, there is the BASE scenario, which includes RGGI and other existing climate policies, and the TCI scenario, which includes the TCI program in addition to all baseline policies included in BASE. The second set of scenarios include BASE-EXT and TCI-EXT and assumes both TCI and RGGI extend their annual emissions reduction trends through 2050. This set of scenarios is designed to explore the potential impacts of the continuation of TCI’s and RGGI’s reduction trends.

Both BASE and BASE-EXT serve as reference scenarios in which the transportation sector evolves without additional transportation constraints, other than CAFE and the ZEV targets, along with annual CO₂ caps on electricity generation governed by RGGI are all included in these baseline scenarios. RGGI constraints after 2020 were updated, as RGGI currently undergoes an expansion in its membership, with New Jersey having joined the consortium in 2020 and Virginia joining in 2021. Annual RGGI CO₂ constraints for years after 2020 were provided by the Environmental Protection Agency through a simulation from an Integrated Planning Model²⁰. Table 2 summarizes annual constraints that are applied in each scenario.

SCENARIO/TON CO ₂	2020	2025	2030	2035	2040	2045	2050
BASE-RGGI	56.43	86.39	71.17	71.17	71.17	71.17	71.17
BASE-TCI	NA	256.72	228.25	190.78	190.78	190.78	190.78
TCI-RGGI	56.43	86.39	71.17	55.92	40.66	25.41	10.16
TCI-TCI	NA	256.72	228.25	190.78	153.30	115.87	78.39

Table 2. Program constraints

¹⁹ A sunset constraint refers to the constraint in the year, after which the program is no longer effective. In this case, RGGI sunset constraint is the annual constraint applied in 2030, whereas TCI sunset constraint is the constraint applied in 2032.

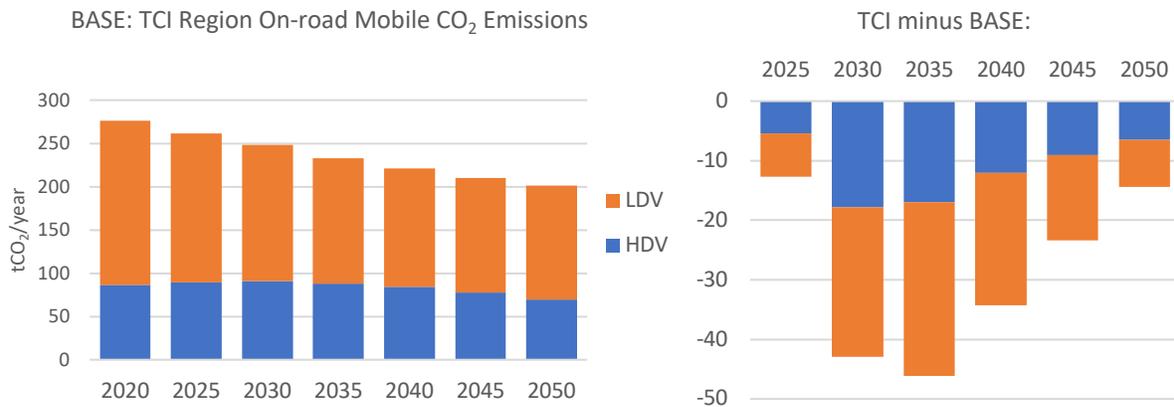
²⁰ Power Sector Modeling. EPA, 2021

Results

Impacts on Regional CO₂ and Air Pollutant Emissions (Scenarios: BASE, TCI)

Within the TCI region, a 30% reduction in on-road transportation CO₂ emissions from 2023 to 2032 is projected to lower annual regional on-road transportation CO₂ emissions by up to 22.8% (55.16 million ton CO₂) from BASE in 2032, with approximately 20% reduction in emissions from heavy-duty vehicles (HDV) and 24% reduction from light-duty vehicles (LDV) (Figure 1.i). However, up to 12.6% of this emissions reduction from on-road mobile services (5.57 million ton CO₂) is offset by increases in CO₂ emissions from other sectors, with the highest increases observed in electricity generation and non-road transportation (Figure 1.ii)²¹. Regionally, TCI has the potential to reduce total emissions by approximately 5.8% among all jurisdictions in 2032.

(i)



(ii)

²¹ GCAM captures biomass emissions as negative values to be consistent with the RGGI mandate. A negative emissions value reported by GCAM suggests positive emissions.

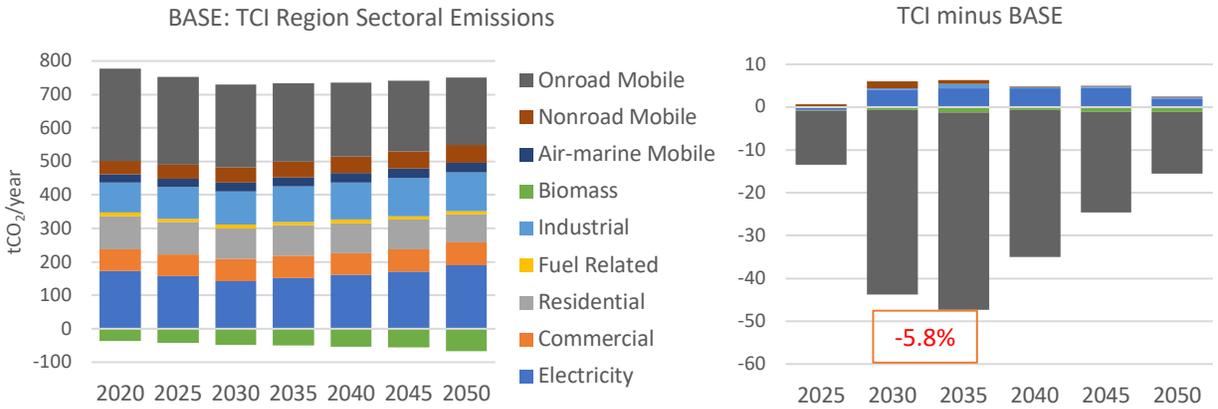


Figure 1. (i) Summary of TCI’s impact on regional on-road transportation CO₂ emissions by service type; (ii) Summary of TCI’s regional impact on sectoral CO₂ emissions; percentage changes calls out net emissions change in 2032

Results show that TCI not only reduces CO₂ emissions, but would also lower NO_x emission in participating jurisdictions, creating co-benefits from improved in air quality. TCI reduces regional total NO_x emissions by approximately 8.2% in 2032, and state-wide emissions reduction ranges from 5% to 13% (Table 2). Pennsylvania (PA), as the only non-RGGI state in TCI, has the greatest emissions among TCI jurisdictions (Figure 2). However, while NO_x reductions occur in all TCI states, Pennsylvania experiences the least benefit from a percentage standpoint. PA has relatively more pollution coming from non-road transportation services and electricity generation than other states. Similar analysis on TCI’s impact on regional emissions of particulate matter (PM_{2.5}) and sulfur dioxide (SO₂) suggest that TCI has small impacts on these pollutants, with a 0.5% reduction in PM_{2.5} emissions and 1.3% reduction in SO₂ emissions.

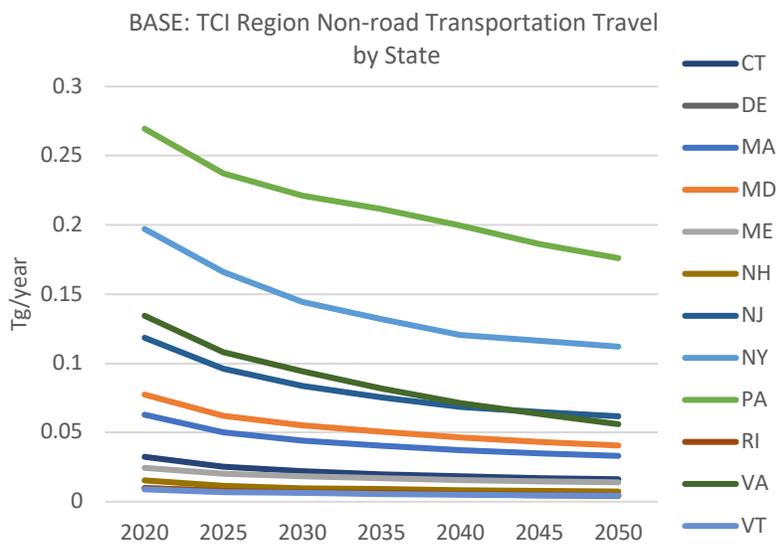


Figure 2. Baseline TCI Region NO_x emissions by state.

STATE	% CHANGE IN NO _x EMISSIONS IN 2032
CT	-10%
DE	-10%
MA	-10%
MD	-9%
ME	-8%
NH	-10%
NJ	-10%
NY	-8%
PA	-5%
RI	-10%
VA	-13%
VT	-10%
TOTAL	-8.2%

Table 3. TCI impacts on state NO_x emissions in TCI Region

Impacts on Regional Transportation Output and Fuel Mix

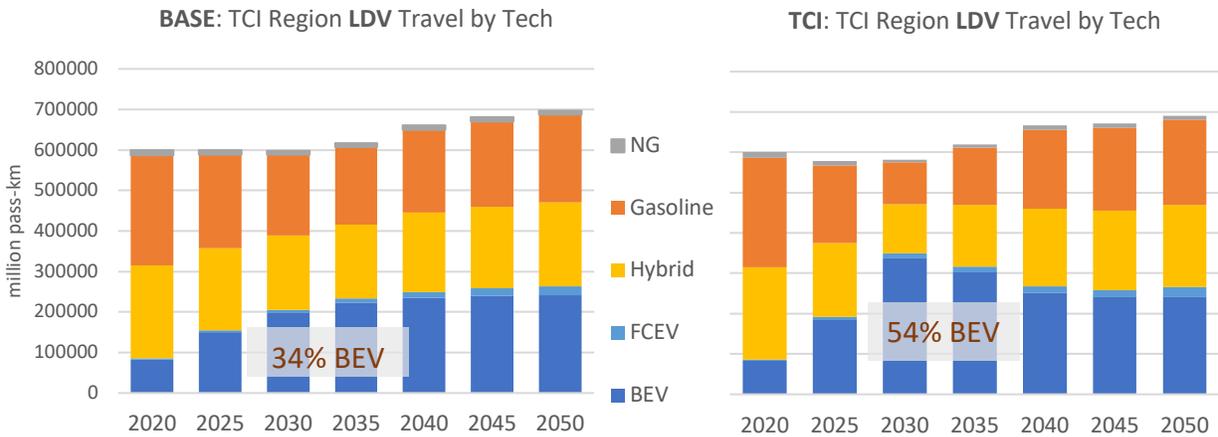
CO₂ emission reductions from on-road transportation could be the result of a combination of market responses to TCI. The first change in the market structure is an increase in the share of electric vehicle (EV) on-road travel demand in both heavy- and light-duty services. By 2032, TCI increases EV share of HDV on-road transportation demand from 18% in BASE to 38%, and share of LDV demand from 34% to 54%.

However, while EV penetration grows between 2023 and 2032, total regional on-road travel demand declines, with an approximately 15% reduction in HDV travel and 1.4% reduction in LDV services in 2032 (Figure 2.i, 2.ii). The relatively large decline in HDV on-road travel suggests that HDV EV technologies are still sufficiently more costly than conventional trucks. The model responds to the higher cost of HDV travel by shifting a fraction of this freight services to other modes.

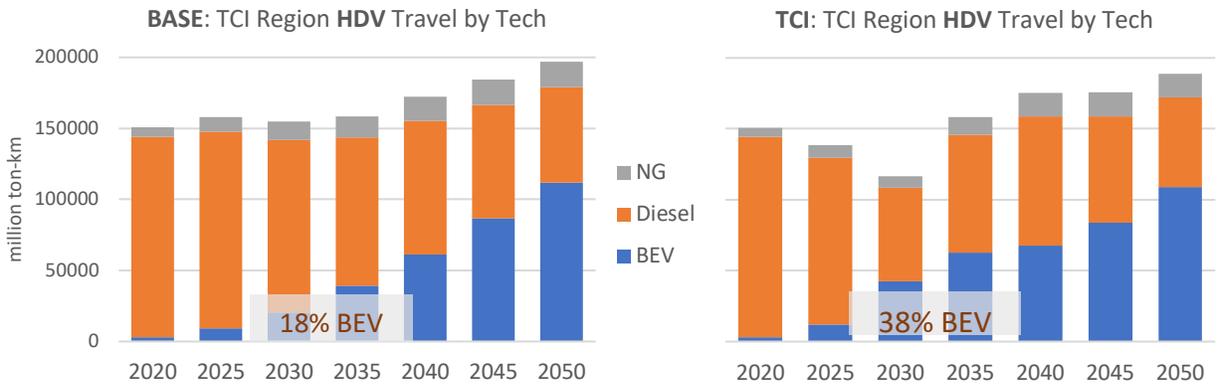
However, results show that the decrease in on-road HDV travel (23,000 million ton-km) is more than compensated by an increase in non-road diesel-fueled services (52,000 million ton-

km). Moreover, the increase in non-road heavy-duty services, such as rail, is over twice as large as the reduction that occur from HDV travel (Figure 2.iii). As a result, TCI causes an increase in non-road transportation CO₂ emissions, which partially offset the emissions reductions from on-road mobile services achieved by TCI (Figure 1.ii).

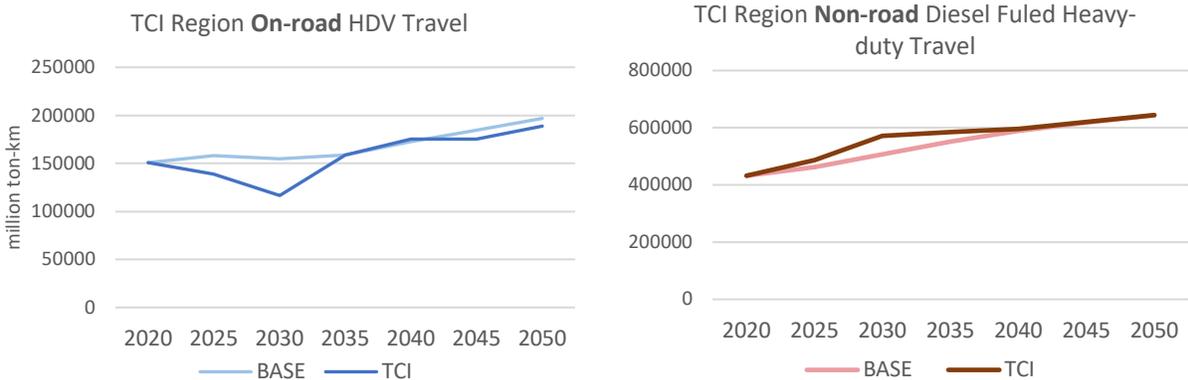
(i)



(ii)



(iii)



(iv)

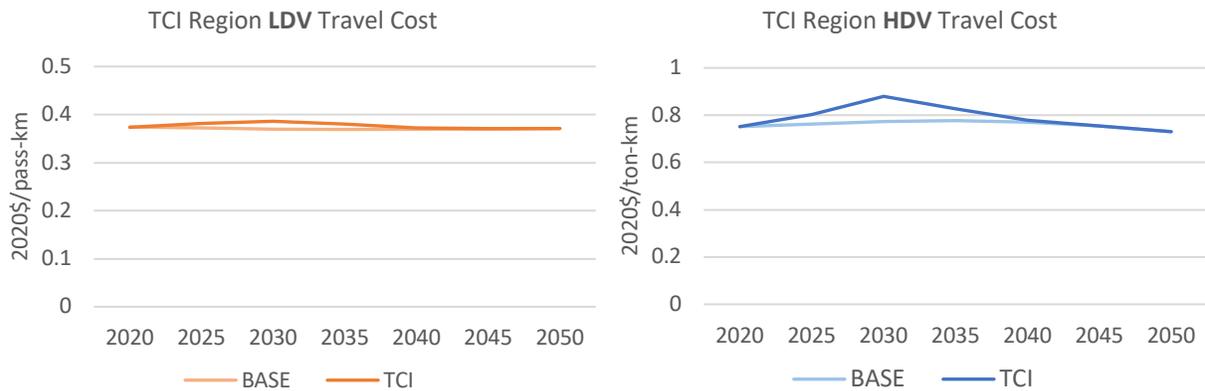


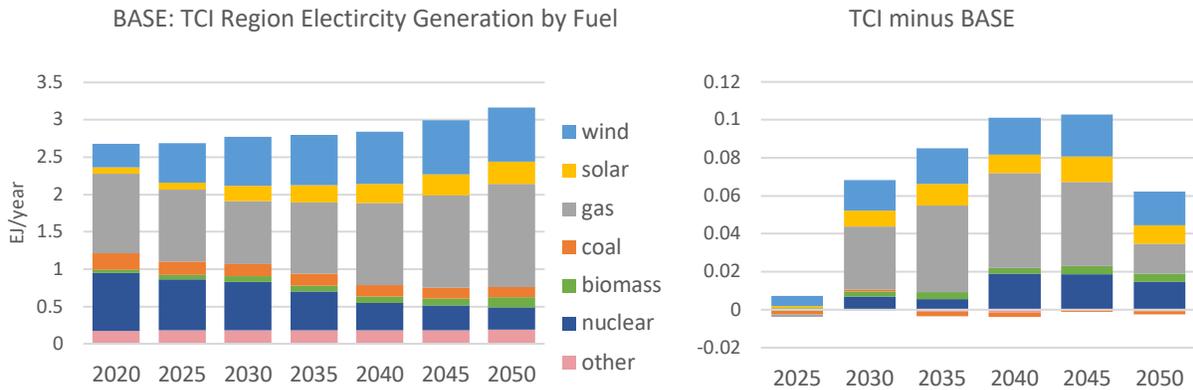
Figure 3. (i) TCI impacts on on-road LDV travel demand by technology; (ii) TCI impacts on on-road HDV travel demand by technology; (iii) TCI impacts on heavy-and light-duty transportation demand; (iii) TCI impacts on heavy-duty travel across service type; (iv) TCI impacts on transportation cost

The electrification of on-road transportation services raises travel costs for both HDV and LDV travel, with a more significant impact on HDV with an 7.9% price increase, compared to a 3.1% increase for LDV (Figure 2.iv). The higher increase in HDV travel cost confirms that HDV EV technologies are yet to be sufficiently affordable and explains the demand shift from on-road to non-road freight services that was shown above. Whereas, the relatively small changes in LDV travel cost suggest that LDV EV technologies are sufficiently affordable and accessible that they could nearly fully absorb the travel demand that shifted away from gasoline-fueled transportation services.

Effects on Regional Electricity Consumption and Generation

As expected, the electrification of the transportation sector raises regional demand for electricity, causing a slight increase of 2.6% in total electricity generation in TCI region. While the impact on total electricity production is small, a large portion of the added electricity demand is supplied using NG, at approximately 38% in 2032, which grows to 47% in 2050. The rest of the electricity supply comes from a combination of wind, solar, nuclear, and biomass energy (Figure 4.i).

(i)



(ii)

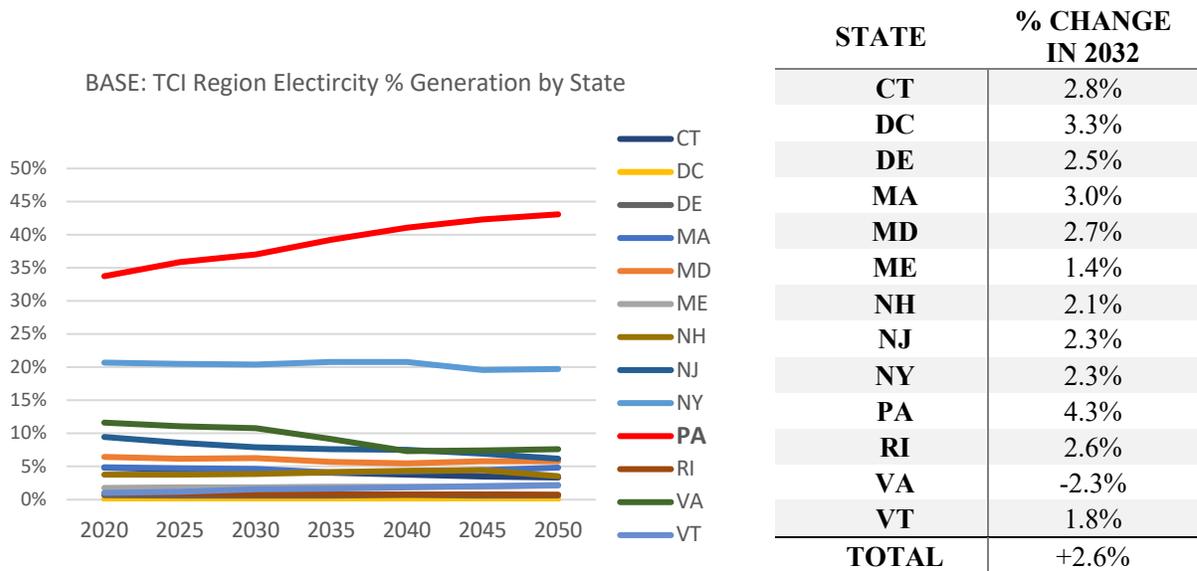


Figure 4. (i) TCI impact on regional electricity demand by fuel mix; (ii) TCI impacts on regional electricity generation by state.

Table 4. TCI impact on electricity generation charge by state

All TCI jurisdictions except Virginia experience a slight increase in electricity generation. In contrast, VA generation drops by 2.3%. PA, the only TCI member state that does not face RGGI constraints on CO₂ emissions from electricity generation, has the highest CO₂ emissions from electricity generation in BASE. Furthermore, PA also experiences the largest percent increase in its state-wide production, with an 4.3% (0.045 EJ) increase in 2032 (Table 4).

TCI Impacts on CO₂ and Regional Electricity Prices

Recall that all but two TCI jurisdictions are also the members of RGGI, under which CO₂ emissions from electricity generation are capped and requires purchase of emissions allowance to be accounted for. The increased penetration of EVs drives up regional demand for electricity, which is partially generated using carbon-intensive fossil fuels, such as coal and gas, as shown in Figure 4(i). The increase in electricity generation using fossil fuels that produce CO₂ emissions raises the RGGI CO₂ allowance price by approximately 13.2% in 2032 (Figure 5).

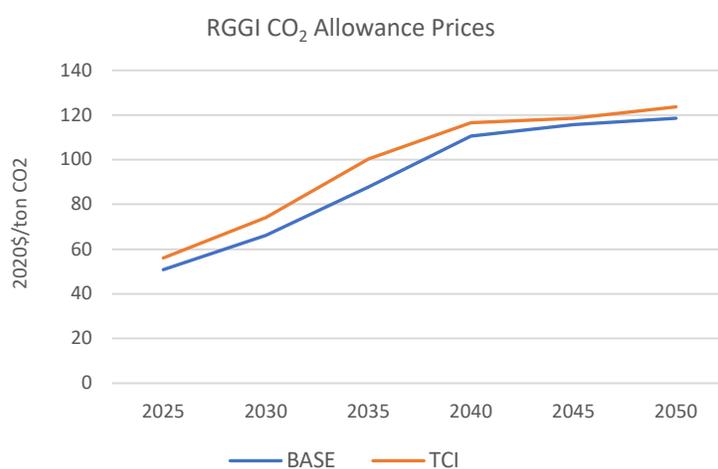


Figure 5. TCI impact on RGGI market CO₂ allowance price

Electricity Grid (2020\$)	BASE Price (cents/kwh)	TCI Price (cents/kwh)	TCI Impact
Mid-Atlantic	15.27	15.64	2.4%
New England	17.10	17.51	2.5%
New York	15.50	15.94	2.8%

Table 5. Summary of TCI impact on grid electricity prices in affected grids in 2032.

The remainder of the power needs are satisfied using renewable technologies. The added production costs arose from the purchases of emissions allowances at a higher price and the higher costs associated with higher market penetration of renewable technologies. The increased

CO₂ cost associated with electricity generation is then partially passed down to consumers, in the form of higher electricity prices. Nonetheless, the results show that TCI has only a small effect on grid electricity prices in participating regions. In 2032, all three of the Mid-Atlantic, New York, and New England grids each experience less than 3% increase in electricity prices. Mid-Atlantic grid electricity price increases by approximately 2.4%, from 15.3 cents/kilowatt hour (kwh) to 15.6 cents/kwh; New England experiences an increase of about 2.5%, from 17.1 cents/kwh to 17.4 cents/kwh; New York’s electricity price raises from 15.5 cents/kwh to 16 cents/kwh, reflecting a 2.8% increase (Table 5). While TCI’s impacts on electricity prices are small, these costs could yet be reduced with more aggressive assumptions regarding solar and wind cost declines over time.

Extended scenario impact on CO₂ and Air Pollutant Emissions

The extended (-EXT) scenarios assume that RGGI (and TCI in TCI-EXT) continue their linear emissions reduction trends until 2050. In the extended policy scenario, while RGGI continues to impose increasingly stringent caps in BASE-EXT, TCI-EXT creates additional emissions reduction from on-road transportation of an approximately 73% in 2050. Regionally, TCI lowers regional emissions by 21% in 2050 from BASE-EXT.

TCI-EXT Impacts on CO₂	Relative to BASE-EXT in 2050
TCI Region on-road transportation CO ₂	-73.3%
TCI regional total CO ₂	-20.9%
Sectoral CO ₂ leakage from transportation	-9.8%
Electricity	+16.1%
Non-road Travel	-0.4%
Leakage to non-TCI Region	0.3%

Table 6. TCI-EXT impact on CO₂ Emissions

Like TCI, while TCI-EXT produces emission reductions in on-road transportation, it also causes sectoral leakage to other sectors of the economy. For example, CO₂ emissions from electricity generation increases by about 16% in 2050. Increases in emissions from other sectors offset about 10% of the CO₂ reductions achieved from on-road transportation, leaving a 21% net CO₂ emissions reduction in all TCI jurisdictions. In contrast to what we observed in the results of BASE and TCI, the increase in non-road mobile services is significantly dampened and reversed by 2050 under TCI-EXT. As shown in Table 3, TCI causes minimal emissions leakage to non-TCI states even when the emission reduction period is extended, and more reduction is achieved.

Previous results (Table. 2) shows that TCI produces co-benefit from simultaneously reducing air pollutant emissions, specifically NO_x emissions. Table 4 shows that TCI-EXT has the potential to further reduce NO_x emissions, by mostly 15% in 2050, while its effects on PM2.5 and SO₂ emissions remain small with less than 2% reduction in PM2.5 and less than 1% reduction in SO₂.

Air Pollutant Emissions	BASE in 2023 (Tg)	TCI in 2032 (Tg)*	TCI-EXT in 2050 (Tg)*
NO _x	0.87	0.69 (-8.2%)	0.44 (-14.9%)
PM2.5	0.13	0.12 (-0.5%)	0.12 (-1.4%)
SO ₂	0.38	0.38 (-1.3%)	0.35 (-0.9%)

Table 7. Summary of TCI impact on regional air pollution emissions; *percentage changes indicate changes in emissions compared to BASE and BASE-EXT

Extended Policy Impact on EV Travel Share

The additional CO₂ reductions from on-road transportation mainly result from the continuous increase in EV technology penetration from 2032 through 2050. By 2032, TCI raised LDV and HDV EV penetration to 54% and 38%, respectively. Nevertheless, the continuation of the annually declining emissions caps further raises the cost of gasoline and diesel-fueled on-

road transportation. As a result, TCI-EXT further increases LDV EV travel share to 91% and induces a complete energy transition from carbon-based fuels to electricity in HDV travel (Figure 5.i, 5.ii). Due to some unforeseen, complex market dynamics, LDV EV penetration declines for a short period after 2030. Further research should address this issue, starting with assessing LDV technology development trends.

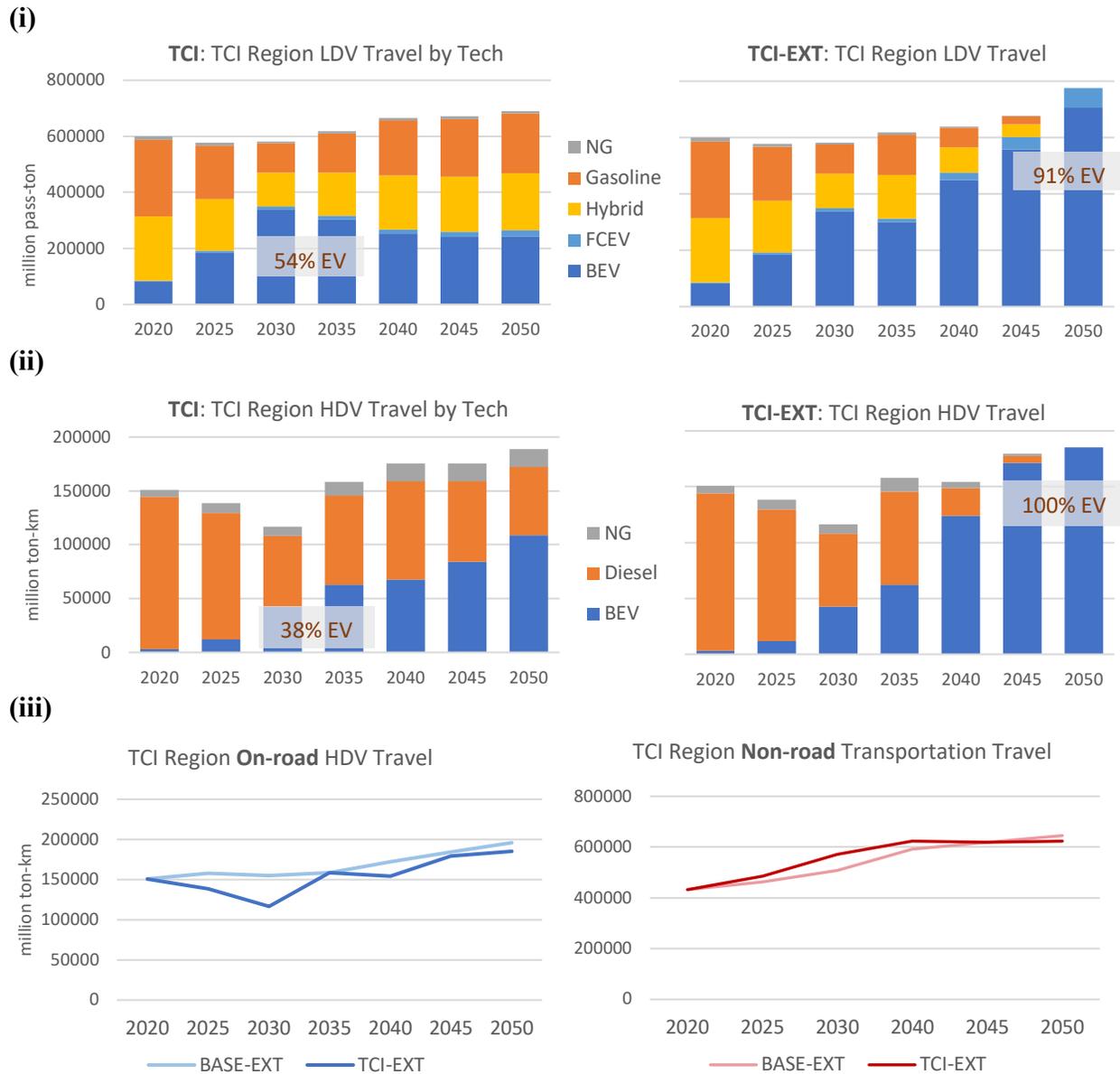


Figure 5. (i)&(ii) Summary of TCI impact on EV share of on-road travel; (iii) Summary of TCI-EXT impacts on heavy-duty travel by service type

While we observe earlier that TCI causes increases in non-road transportation travel in the twenty years after the program is launched, result shows that the impact on non-road mobile services is significantly dampened and even reversed between 2040 and 2050 (Figure 5.ii).

Extended Policy Impacts on CO₂ and Electricity Prices

While the TCI program caused small raises in grid electricity prices from 2023 to 2032 in the Mid-Atlantic, New England, and New York grids, the extended annually declining emissions caps from both TCI and RGGI resulted in greater impacts.

Electricity Grid	TCI Price in 2032 (cents/kwh)	TCI-EXT Prices in 2050 (cents/kwh)	Change from 2032 to 2050	Change from BASE- EXT to TCI-EXT (2050)
Mid-Atlantic	15.6	17.8	14%	0.9%
New England	17.5	25.4	45%	0.4%
New York	15.9	25.4	59%	1.6%

Table 8. Summary of TCI impact on grid electricity prices in affected region

In 2032, TCI slightly increased electricity prices to a range between 15.6 cents/kwh in Mid-Atlantic grid and 17.5cents/kwh in the New England grid. While grid electricity prices significantly grow between 2032 and 2050, much of the increases are the result of the ever-more-stringent RGGI caps, rather than those of TCI. In 2050, the extended TCI scenario (TCI-EXT) only causes an increase between 0.4% and 1.6% in grid electricity prices from the baseline scenario (BASE-EXT). New York experiences the largest impact with an 1.6% increase, whereas New England and Mid-Atlantic see increases of 0.4% and 0.9%, respectively (Table 8).

Discussion

Uncertainties

Results show that a thirteen-state TCI has the potential to significantly reduce regional CO₂ emissions with a slight increase in power and transportation emissions and costs. However,

since TCI is still under development, and RGGI is undergoing an expansion in member states, there are several uncertainties around both programs that have the potential to influence the TCI's efficacy and impacts.

The first uncertainty about this newly proposed policy is regarding its membership. On the one hand, there exist uncertainties on whether TCI member states will participate in the voluntary cap-and-invest program. To date, four of the TCI member-states, Connecticut, D.C., Massachusetts, and Rhode Island, have signed the Monument of Understanding (MOU) for TCI and are planning on launching a 4-state TCI program in 2023. While a smaller scale TCI program has the potential to reduce emissions within participating jurisdictions, the four jurisdictions mentioned above contribute a small portion of TCI region's total emissions. Therefore, a fewer-jurisdiction-TCI program is unlikely to have a significant impact on regional total emissions. On the other hand, TCI could experience expansion membership from neighboring states. For instance, the state of North Carolina has initiated its clean energy plan, which introduces the possibility of participating in TCI.

RGGI membership has also changed over time. New Jersey, as one of the first states to join RGGI in 2009, exited the program in 2011 and has now rejoined. Along with the expecting addition of Virginia in 2021, this indicates uncertainty in membership as well. As shown in the results in this paper, PA disproportionately experiences increase in electricity demand and the least air pollution co-benefits because it does not have a constraint on electric sector CO₂ emissions like other TCI states. The state has expressed interest in joining RGGI but has yet to officially announce the plan. Similar to TCI, RGGI has the potential to expand to neighboring states, such as North Carolina, which is already in the process of energy transition away from fossil fuels.

Another uncertainty is the assumption about consumer bias towards EVs. Electric vehicles are relatively new but fast-growing products in the transportation sector. Given their shorter history for on-road passenger transportation, consumers often are more familiar with and preferred conventional, gasoline or diesel-fueled cars over EVs. In addition, there are also concerns regarding the charging time, availability of charging infrastructures, and range limits. GCAM captures this consumer bias by assigning a share-weight to each available technology, where a share-weight of 1 indicates consumers are no longer biased against that particular technology. Previous results assumed that, in an era where climate mitigation and GHG emissions reduction are among the world's most urgent tasks, consumer biases and other barriers for EV adoption will no longer exist after 2035. However, it is uncertain when and how this bias would disappear. To explore how the uncertainty around consumer EV bias can affect TCI's performance, I evaluated another case, where the share-weights for both HDV and LDV EV technology do not reach 1 until 2050. Results suggest that a more conservative assumption about consumer's change of attitude toward EV leads to larger sectoral and regional CO₂ leakage within and outside of the TCI region (Table 1. Supplementary Information).

Comparison to Georgetown Climate Center Results

As mentioned earlier in the paper, the GCC assumed aggressive political support for climate policies that are likely to grow low-carbon technology accessibility while reduce costs in the near future. More importantly, the Georgetown study includes the investment of program revenue as part of their study using the TCI investment strategy tool. The research team reported that the CO₂ allowance cost in the TCI market would be in a range between \$10-\$20/tCO₂. This study reports that the CO₂ cost would range from \$135/tCO₂ up to \$427/tCO₂, in absence of the investment component (Graph 1. Supplementary Information).

Caveat & Future research

While this study investigates the emissions reduction potential and impacts of TCI's emissions caps, it does not take into consideration the potential effects of the investments that are expected to be funded by the revenue generated from allowance auctions. These investments are another significant component of TCI's cap-and-invest program. Program revenue is expected to fund equitable and low-carbon transportation projects, such as improving and building existing and new transportation infrastructures to make public transportation more accessible, investing in low-carbon transportation technologies to lower R&D cost for producers, and subsidizing these technologies to make electric vehicles more affordable. These investments have the potential to aid the transportation sector's the energy transition from carbon-intensive fossil fuels to lower-carbon electricity by reducing the cost of compliance. Given these hypotheses, the results on transportation, electricity, and CO₂ costs presented in this paper are likely overestimates of what the costs would be after implementation. However, the significant increase in HDV travel cost indicates that electric heavy-duty vehicles can be a potential target for investments. In addition to addressing the peculiar market dynamics that cause the dip in LDV EV penetration after 2030, future research could potentially investigate the impacts of alternative investment portfolios that can address equity, accessibility, and affordability issues.

Conclusion

The GCAM-USA v5.2 human-Earth integrated model is applied to conduct an analysis of the emissions reduction potential, impacts on regional markets, and co-benefits of the Transportation and Climate Initiative (TCI). The hypothesis that constraining CO₂ emissions from the transportation sector could interact with the RGGI market appears to be true. The results show that while TCI is effective at reducing on-road transportation emissions, it also

causes sectoral emission leakage to electricity and non-road transportation services in the short term. The increased electricity demand drives up RGGI's CO₂ allowance price, which leads to minor increases in regional electricity prices. Results from this study also confirm previous research's finding that TCI could create co-benefits through emissions reductions of air pollutants that are co-products of CO₂ during combustion, such as NO_x.

Results of the extended policy scenario show that extending both RGGI's and TCI's emissions reduction trends to 2050 significantly improve regional CO₂ and NO_x emissions reductions. At the same time, the extended TCI program has the potential to aid the complete energy transition from fossil fuels to electricity among on-road transportation services. The extended scenario causes an increase in grid electricity prices within the TCI region, with the largest jump in New York. However, this relatively big change in price is likely the result of the extended RGGI program, given that TCI-EXT does not cause much of an impact from the baseline scenario.

While uncertainties around technological advancement, cost, and consumer bias could affect the performance of TCI, results show that, overall, TCI is an effective program at reducing regional CO₂ emissions and promoting the energy transition away from fossil fuels among on-road transportation services. While the program causes some sectoral emissions increases within the TCI region, it causes minimal emission leakage to non-TCI states. In addition, extending RGGI's annual reduction along with TCI's through 2050 significantly improves the programs' joint effectiveness at reducing regional CO₂ and NO_x emissions.

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Supplementary graphs and tables

Table 1. Result with consumer bias toward EV disappear after 2050

TCI (EV SW=1 IN 2050)'S IMPACTS ON CO2 IN 2032	RELATIVE TO BASE (EV SW=1 IN 2050)
TCI REGION ON-ROAD TRANSPORTATION CO2	-27%
TCI REGIONAL TOTAL CO2	-7%
SECTORAL CO2 LEAKAGE FROM TRANSPORTATION	25%
LEAKAGE TO NON-TCI REGION	4%