Forecasting

CLIMATE ACTION FRAMEWORK 2026

cc-mn4-04e

Climate Action Framework forecasting technical support document:

Greenhouse gas emissions, health, and economics

Report to the Minnesota Legislature, February 2026, submitted by the Pollution Control Agency.

Legislative charge

Laws of Minnesota 2023, chapter 60, article 1, section 2, subdivision 2 Pollution Control Agency.

Subdivision 2, part (j) $500,000 the first year is to facilitate the collaboration and modeling of greenhouse gas impacts, costs, and benefits of strategies to reduce statewide greenhouse gas emissions. This is a one-time appropriation.

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Special thanks to the external participants of the Modeling Workgroup for sharing their expertise.

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Estimated cost of preparing this report, as required by Minn. Stat. § 3.197:

Legislative funding	$500,000
Climate Pollution Reduction Grant (CPRG) funding	$75,000
Modeling contract, paid with legislative and CPRG funding	-$452,996
Agency overhead from legislative funding	-$122,004

Contents

Executive summary

Minnesota has statutory goals to reduce statewide greenhouse gas (GHG) emissions to net zero by 2050, with an interim target of a 50% reduction by 2030 relative to a 2005 baseline, and additional statutory goals for transportation emissions. Assessing projected emissions of GHGs and co-pollutants under current and potential government policies is critical to understanding how different actions could reduce emissions, while accounting for costs and prioritizing economic benefits and health impacts for Minnesota communities.

In 2023, the MPCA requested and received state and federal funding for GHG emissions forecasting and benefits analysis of climate pollution reduction strategies. A GHG emissions forecast is an estimate of future GHG emissions based on assumptions about policies, populations, economic growth, and other activities that influence emissions. Forecasting helps define GHG reduction targets, estimate potential emission reductions from specific climate actions, and plan long-term climate actions. In addition, the Climate Change Subcabinet completed health and economic modeling based on the GHG emissions forecasting. Together, GHG forecasting and health and economic modeling are tools to help better understand different options and foster more effective climate policy decision-making.

The MPCA, with guidance from the Climate Change Subcabinet, worked with the University of Maryland Center for Global Sustainability to forecast GHG emissions using the state-level version of the Global Change Analysis Model (GCAM-USA). Emissions and sequestration from agriculture and land use, land-use change, and forestry (LULUCF) were forecasted in a parallel process led by the MPCA, with input from the interagency Natural and Working Lands Goal Team and integrated with GCAM-USA. This forecasting work complements the state's biannual GHG emissions inventory, which estimates historical emissions to track progress towards the state's carbon-neutrality goal. The Climate Change Subcabinet also guided health and economic forecasting, building on the GHG forecasting work.

Annual GHG emissions and sequestration within Minnesota were projected through 2050 under three core scenarios:

- **Current Policies scenario:** This scenario estimates how effective current actions and state and federal laws could be in progressing towards carbon neutrality.
- **Potential Policies Pathway scenario:** This scenario illustrates a set of policies used in other states or countries that could get Minnesota substantially closer to its GHG emissions reduction goals (Table 1). The impacts of policies and actions modeled in this scenario may interact across the Climate Action Framework goals. This scenario was developed in a bottom-up process, meaning the model considered a suite of ambitious potential policies to add on top of current policies. Importantly, the policies and actions modeled in this scenario do not represent advocacy or intention on behalf of the Climate Change Subcabinet. Instead, this scenario helps illustrate the pace and scale of action needed to achieve Minnesota's climate goals. Finally, within this scenario, the term "policy" is used broadly to encompass a collection of actions, a desired outcome, or a statutory or regulatory framework. Modeling policies in this way allows for flexibility in the mechanisms of action, should they be implemented.
- **Net-Zero Pathway scenario:** This scenario builds on the Potential Policies Pathway scenario by requiring achievement of Minnesota's GHG emissions goals. The Net-Zero Pathway scenario forces the model to achieve carbon neutrality in Minnesota through the least-cost path and describes impacts, without defining specific policies to achieve it.

Table 1. Categories of state-level policies included in the Potential Policies Pathway scenario.

Sector	Policy category
Transportation	Increase travel options and reduce passenger vehicle use
	Reduce the carbon intensity of transportation energy
Agriculture	Sequester carbon and reduce GHG emissions from agricultural lands
	Reduce nitrogen losses from croplands
	Reduce GHG emissions from manure management and enteric fermentation
Land use, land-use change, and forestry	Sequester more carbon in landscapes and products
	Prevent loss of sequestered carbon in landscapes
Industrial	Provide market incentives for cost-effective mitigation
	Explore efficiency, electrification, and alternative energy sources
Waste	Reduce methane emissions from waste
	Divert and redirect waste
Commercial and residential buildings	Improve building efficiency

The federal climate policy landscape changed dramatically during the framework update process. Therefore, two variations were developed to help make sense of the path forward:

- **Before 2025 federal climate rollbacks**, includes all climate investments in the Inflation Reduction Act and the Infrastructure Investment and Jobs Act, and pre-2025 Clean Air Act climate rules.
- **After 2025 federal climate rollbacks** removes the climate investments in the Inflation Reduction Act and Infrastructure Investment and Jobs Act that were rescinded in 2025. This variation also includes substantial Clean Air Act rule changes proposed by the Environmental Protection Agency (EPA), including changes in GHG emission rules for electric generating units and vehicle emissions standards. While these Clean Air Act rule changes are not yet complete, including them in the federal climate rollbacks scenario reflects the outcome of their implementation.

Key takeaways from GHG forecasting and economic and health analysis

Key takeaway #1. Minnesota is reducing GHG emissions, but achieving the statutory goals will require an increased pace and scale of climate action across all sectors.

The modeling efforts demonstrated the significant pace, breadth, and scale of action needed to meet statewide emissions-reduction targets. The model results indicated that implementing current state and federal policies will put Minnesota on track to reduce GHG emissions by approximately 28% in 2030 and 39% by 2050 relative to the 2005 baseline (Figure 1). Alternatively, implementation of the Potential Policies Pathway scenario would put Minnesota on track to reduce emissions by approximately 35% by 2030 and 77% by 2050 relative to the 2005 baseline (Figure 1). The Net-Zero Pathway aligns with the 2030 and 2050 statewide statutory GHG goals (Figure 1). Significant emission reductions can be achieved compared to our current trajectory in the transportation and industrial sectors through policies that reduce fossil fuel consumption, and in the agriculture and land use, land use change, and forestry sectors through changes to agricultural and land management practices (Figure 2).

Figure 1. Historical statewide net GHG emissions (2005-2020) and projected (2020-2050) net emissions under the Current Policies, Potential Policies Pathway, and Net-Zero Pathway scenarios.

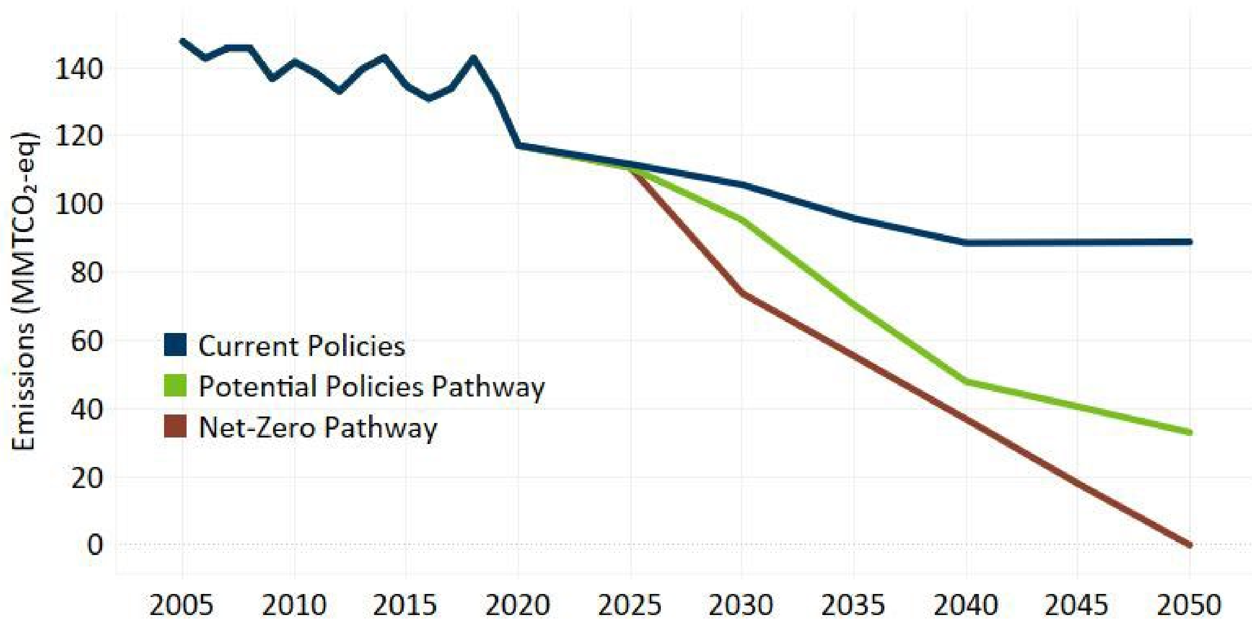
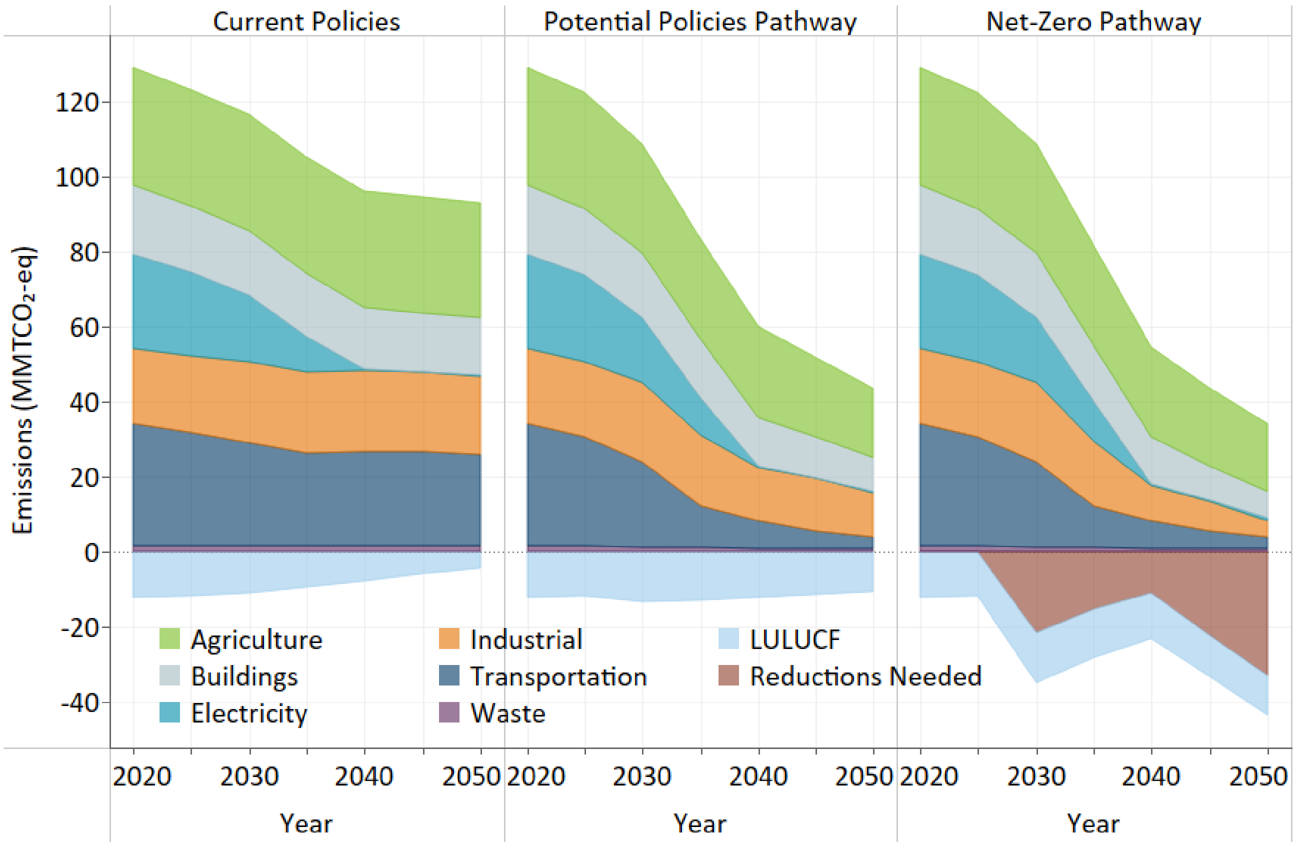


Figure 2. Expected statewide emissions by economic sector under the Current Policies scenario, Potential Policies Pathway scenario, and Net-Zero Pathway scenario.

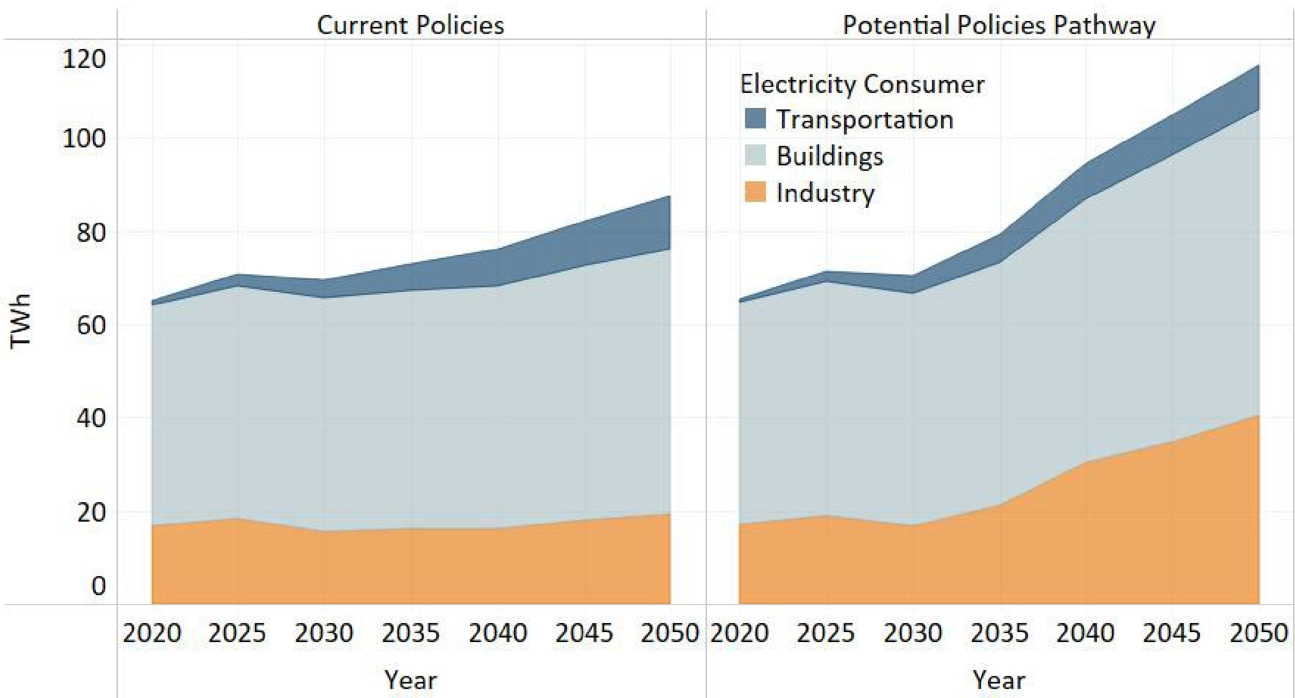
"Reductions Needed" represents additional emissions reductions necessary to meet Minnesota's emissions reduction targets that are not achieved under the constraints of the Net-Zero Pathway. The timing of anticipated electricity-sector emissions reductions by 2040 strongly influenced the irregular need for additional unidentified sources of reductions over time.



Key takeaway #2. Decarbonizing and expanding electricity generation are essential to achieving Minnesota's GHG emission reduction goals.

Reducing GHG emissions from transportation, buildings, and industry requires making processes more efficient and using clean electricity to power these sectors. Switching from equipment that burns fossil fuels to electric equipment will require generating more electricity, but it is a cleaner energy source. The forecast shows that to make rapid progress toward state goals, Minnesota needs to continue reducing GHG emissions in the electricity sector and increase clean electricity production to power other sectors (Figure 3). Notably, this increased demand for electricity is forecast to occur in addition to potential demand from new data centers in the state, which could lead to substantial additional demand.

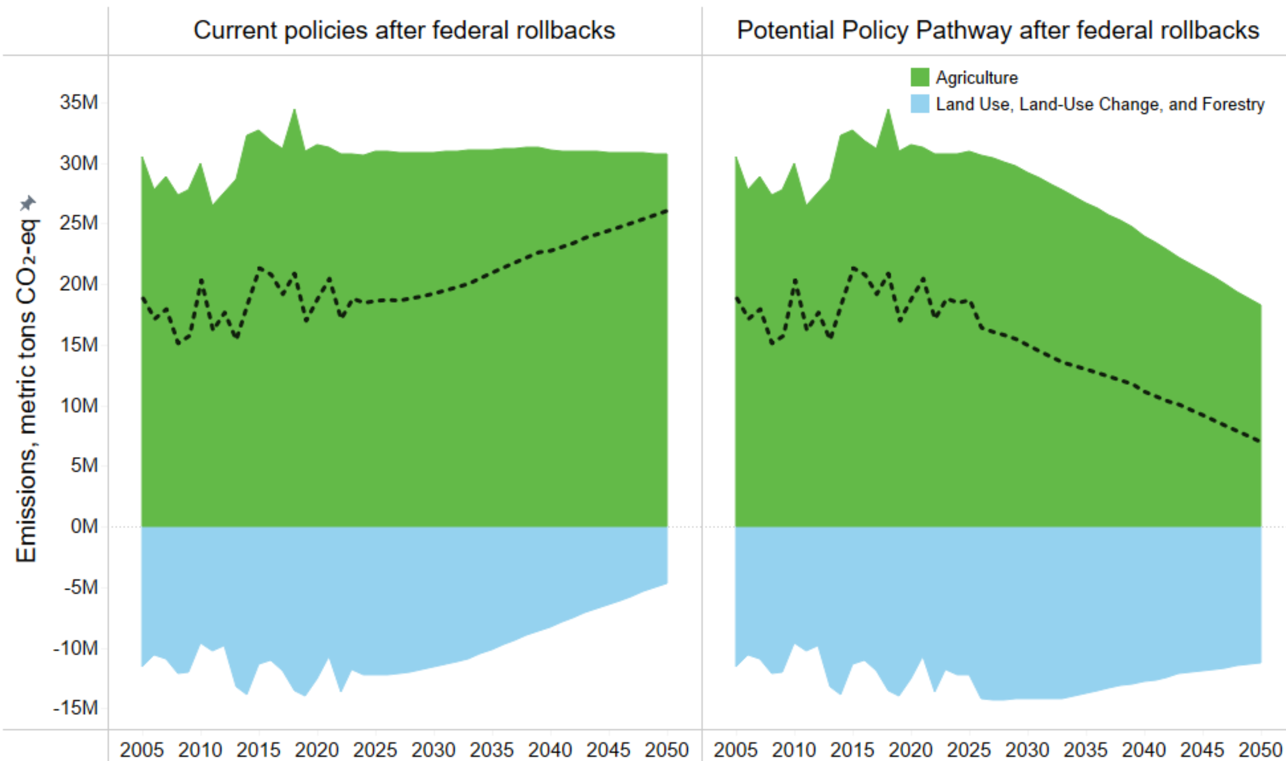
Figure 3. Electricity consumption (TWh) by consumer under the Current Policies and Potential Policies Pathway scenarios.



Key takeaway #3. Sustaining and increasing carbon sequestration in Minnesota's lands will continue to be essential to achieving carbon neutrality and will take added effort to maintain.

Minnesota currently benefits from significant net carbon sequestration in its natural and working lands. Given Minnesota's aging forests and ecological changes driven by climate change, such as increased emissions from warming peatlands, the scale of this sequestration is under threat (Figure 4). While forecasting includes significant uncertainties, it underscores the importance of stewarding healthy lands to maintain carbon sequestration in agricultural soils, forests, grasslands, and wetlands, helping offset GHG emissions in other sectors (Figure 4).

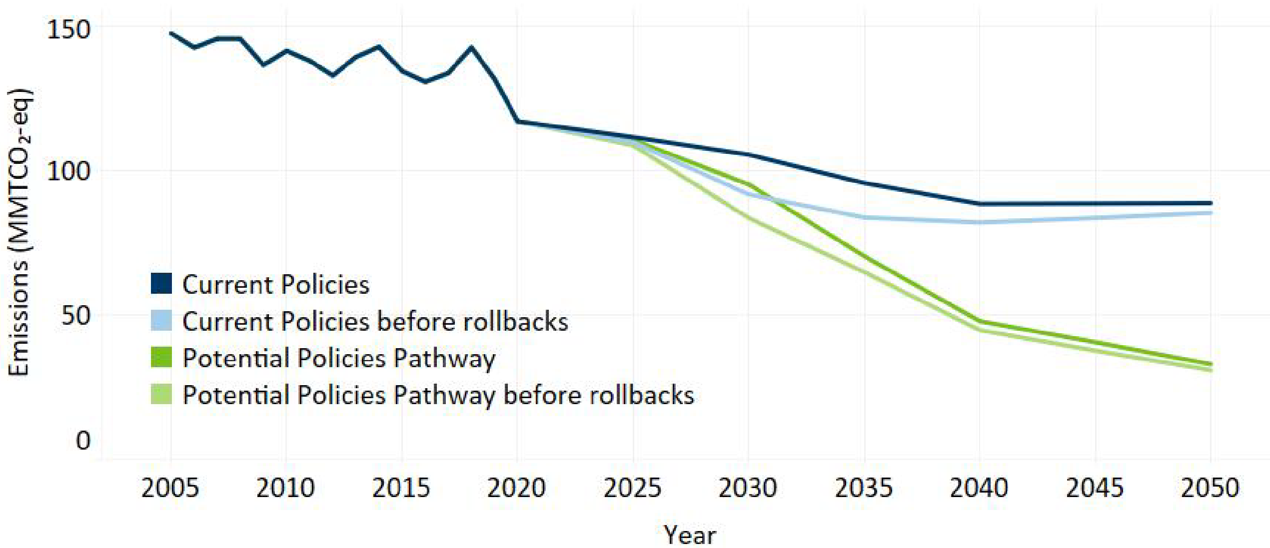
Figure 4. Net GHG emissions from the agriculture (green) and the land use, land-use change, and forestry (blue) sectors under the Current Policies and Potential Policies Pathway scenarios.
The dashed line indicates net emissions from both sectors.



Key takeaway #4. Rollbacks in federal climate investments and regulations will make reducing GHG emissions more difficult and will lead to slower emission reductions in the near-term, higher costs, and worse health outcomes.

Lower federal investment in clean energy and the infrastructure to support its deployment means higher GHG emissions in the near term and a higher cost burden on electricity ratepayers, as federal money for energy infrastructure has been clawed back. Proposed rollbacks to federal regulations that have driven fuel efficiency and the electrification of transportation will make it more challenging to achieve GHG emissions reductions in the transportation sector. This setback will likely leave drivers paying for more gas to travel the same distance in a less efficient vehicle. Figure 5 shows slower GHG emissions reductions after rollbacks in both the Current Policies and Potential Policies Pathway scenarios. Furthermore, the federal rollbacks may result in a loss of $125 million to $160 million in annual monetized health benefits by 2050, leading to more early deaths and other less severe negative health outcomes.

Figure 5. Total GHG emissions under the Current Policies and Potential Policies Pathway Scenarios, before and after federal rollbacks.



Key takeaway #5. Investing in accelerated climate action beyond current policies will make Minnesotans healthier.

The more ambitious Potential Policies Pathway scenario is projected to result in greater improvements in Minnesota's air quality and thus greater health benefits for Minnesotans than the Current Policies scenario, including avoiding early deaths and numerous less severe respiratory and cardiovascular health outcomes, reflecting an annual economic benefit in the billions of dollars. Table 2 presents conservative estimates of the additional annual health benefits in Minnesota from the Potential Policies Pathway scenario relative to the Current Policies scenario from lower pollutant emissions in 2050.

Table 2. Estimated additional annual health benefits in Minnesota in 2050 in the Potential Policies Pathway scenario over the Current Policies scenario resulting from improved air quality.

Health impact	Reduced annual incidence	Economic value ($)
Total health benefits – low estimate	**-**	**$1.17 billion**
Total health benefits – high estimate	**-**	**$2.28 billion**
Mortality – low estimate	86	$1.10 billion
Mortality – high estimate	173	$2.21 billion
Nonfatal heart attacks	39	$2.86 million
ER visits for respiratory issues	93.5	$132,000
Respiratory hospital admissions	10.3	$206,000
Asthma onsets	378	$25.1 million
Asthma symptoms	66,400	$7.64 million
Minor restricted activity days	71,500	$7.86 million
Work loss days	12,000	$3.32 million
School loss days	14,100	$20.8 million

Key takeaway #6. Climate action can be achieved along with strong economic growth and wellbeing.

Modeling indicates that Minnesota can continue reducing GHG emissions while maintaining strong, broad-based economic growth. Under both the Current Policies and Potential Policies Pathway scenarios, gross domestic product (GDP) and personal income steadily increase through 2050, and employment grows across many occupations and industries. As shown in Figure 6, Minnesota has historically decoupled economic growth from emissions, and the modeling results suggest this trend can continue with sustained climate action. In short, reducing emissions and improving health outcomes need not come at the expense of economic prosperity.

Figure 6. Historical and modeled statewide emissions and economic trends under the Current Policies and Potential Policies Pathway Scenarios.

Introduction

Greenhouse gas (GHG) forecasting is the process of estimating future GHG emissions and sequestration based on current trends and assumptions about how emission-relevant activities will change in the future. Effective forecast models combine an understanding of how relevant economic and ecological systems function and respond to change with assumptions about how market or policy-driven changes are likely to influence those systems and, ultimately, GHG emissions. Forecasting enables the holistic examination of complex interactions between economic activities, energy consumption, and environmental outcomes.

GHG forecasting typically models the expected impact of generalized policies and does not specify implementation details. The term "policy" is used broadly to encompass a collection of actions, a desired outcome, or a statutory or regulatory framework, while leaving flexibility in the mechanisms of action (e.g., regulation, financial incentives, funding allocation). As such, forecasting is a tool that can help policymakers and researchers assess the potential outcomes of different climate policies, define areas for further study, and ultimately develop more informed, effective approaches to reducing net GHG emissions.

Several factors have led the state of Minnesota to complete comprehensive GHG forecasting at this time. In 2007, the Minnesota Legislature passed targets to reduce GHG emissions relative to 2005 and strengthened these targets in 2023 (-50% by 2030 and net-zero by 2050). Since 2009, the Minnesota Pollution Control Agency (MPCA) has published biennial greenhouse gas inventory reports. Each report has expanded and improved upon the previous, and these historical emission data serve as a foundation for forecasting. Minnesota's original Climate Action Framework, published in 2022, recommended many GHG mitigation actions across all economic sectors. However, this 2022 framework did not include an assessment of the extent to which those actions would reduce statewide emissions or an estimate of the economic and health impacts. Given this knowledge gap, the Governor and MPCA requested and received funding from the Minnesota Legislature, which was paired with Minnesota's Climate Pollution Reduction Planning Grant from the US Environmental Protection Agency, to complete a GHG forecast as an integral component of the updated Climate Action Framework.

Greenhouse gas forecasting

The MPCA contracted with the University of Maryland Center for Global Sustainability (UMD-CGS) to assist with forecasting GHG emissions of current policies and a set of potential policies that move the state toward statutory GHG emissions reduction targets, using the state-level version of the Global Change Analysis Model (GCAM-USA). Additional variations on these scenarios were also produced to reflect the rollback of federal policies in 2025. Comparing these scenarios enables the state to assess its current policies and identify potential solutions to address climate change and achieve GHG emission reduction goals.

The GCAM-USA model has limited ability to assess the movement of GHGs between Earth's surface and atmosphere (GHG fluxes) and changes in the carbon stored in natural materials like soil, trees, and plants (biogenic carbon stocks) at the spatial scale and boundaries of this analysis. Therefore, the MPCA conducted a parallel forecasting effort for the agriculture and land-use, land-use change, and forestry (LULUCF) sectors. These inventory sectors are often collectively referred to as the natural and working lands sector, as is done in the main body of the Climate Action Framework. This approach improved the breadth of included fluxes and provided greater local specificity at the expense of fully integrating these sectors into economy-wide forecasts. Emissions and sequestration from these agricultural and LULUCF projections served as fixed inputs for integration with the GCAM-USA model, which then derived GHG emission estimates across the rest of Minnesota's economy and activities.

The development of Minnesota's GHG emissions forecast scenarios was an iterative process. The MPCA and UMD-CGS updated the model's inputs and assumptions in response to public feedback and peer review. Analytical teams from various agencies and a public modeling workgroup reviewed the project, scope, assumptions, and results at key points during development to provide expert advice and stakeholder engagement. The broad expertise of contributors and the model development team incorporated the best available information and assumptions about future energy supplies, energy demand, policy implementation, and economic development.

The Potential Policies Pathway scenario was developed based on strategies prioritized through Climate Change Subcabinet guidance, interagency goal-team collaboration, leadership consultation, and public engagement. These are hypothetical policies that could help us meet our goals of supporting energy-efficient, low-carbon, equitable progress, informed by the use of these types of actions by other states or countries; model inclusion does not mean that the state endorses or advocates for any of these policies. The analysis shows impacts of the portfolio of actions on GHG emissions and sequestration, health outcomes, and economic development.

Health and economic modeling

In addition to estimating GHG emissions, the GCAM-USA model estimated changes in co-pollutant emissions that affect Minnesotans' air quality and health from a wide range of industrial sources. These model outputs allowed for the estimation of additional co-impacts alongside reductions in GHG emissions. Using the GCAM-USA co-pollutant estimates as inputs, the EPA's Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) was used to estimate the trajectory of health benefits expected to result from the Potential Policies Pathway and Net-Zero Pathway scenarios. COBRA provides estimates of the health benefits from pollution reduction, both in terms of reduced symptom incidence and monetized values. COBRA estimates how emissions of five different pollutants (fine particulate matter 2.5 micrometers in diameter and smaller ($PM_{2.5}$), ammonia (NH_3), sulfur dioxide (SO_2), nitrogen oxides (NO_X), and volatile organic compounds (VOCs)) translate to changes in concentrations of $PM_{2.5}$ and ozone in the air across Minnesota. While other air pollutants besides $PM_{2.5}$ and ozone affect people's health, these two pollutants are the most widely studied and have the most significant health impacts.[1] COBRA additionally models how changes in these two pollutants translate into changes in human health outcomes at the county level, using both concentration-response relationships from the epidemiological literature and population density data across the state. Finally, COBRA draws on economic valuation literature to assess the economic value of changes in health outcomes.

To assess the economic impacts of the GCAM-USA scenarios, the MPCA worked with the Minnesota Department of Employment and Economic Development (DEED) and Regional Economic Models, Inc. (REMI) to estimate employment, income, and output changes. The analysis was done using REMI's PI+ model, a dynamic modeling tool that integrates input–output, computable general equilibrium, econometric, and economic geography approaches. The model was customized for Minnesota's economy and population, enabling regional analysis across the seven-county Twin Cities metropolitan area and Greater Minnesota.

Results from the GCAM-USA modeling, such as projections of energy use, fuel switching, and clean technology deployment, were mapped to PI+ policy variables and used to estimate downstream effects on consumer spending, business investment, and economic output. While the economic modeling focused on high-level

[1] Minnesota Pollution Control Agency and Minnesota Department of Health. 2019 "Life and breath: How air pollution affects health in Minnesota" https://www.pca.state.mn.us/sites/default/files/aq1-64.pdf (accessed 2025-11-21).

impacts rather than detailed implementation design, it offers a valuable perspective on the scale and distribution of potential economic gains associated with climate action in Minnesota.

Methods: Greenhouse gas forecasting

Forecasting scenarios

Three core scenarios, a Current Policies scenario, a Potential Policies Pathway scenario, and a Net-Zero Pathway scenario, were created to forecast Minnesota's potential greenhouse gas reduction pathways. Each core scenario helped answer questions that are informative for the process of developing policies, such as:

- What would happen to GHG emissions through 2050 if Minnesota continued only with existing policies?
- Which areas or sectors are most promising for policy interventions to achieve greater GHG emissions reductions beyond the current pathway?
- Which policies could help Minnesota move most cost-effectively toward its GHG emissions reduction targets?

In addition, variations of both the Current Policies and Potential Policies Pathway scenarios were modeled to assess the impact of federal changes resulting from the rollback of key climate provisions in 2025. The Net-Zero Pathway scenario was helpful in early discussions to inform priority selection and was subsequently revised to reflect recent developments. For further analysis, a variation of the Potential Policies Pathway scenario without a cap-and-invest policy was created to examine the impact of such a policy. In total, six scenario variations were modeled as described in Table 3, with the specific policies outlined under the GCAM and Agriculture and LULUCF modeling sections, respectively.

Table 3. Core scenarios and variations.

Core scenario	Core scenario description	Scenario variations
Current Policies scenario	This scenario estimated the effectiveness of current commitments and state and federal laws toward achieving carbon neutrality.	1: Current Policies before federal rollbacks 3: Current Policies after federal rollbacks
Potential Policies Pathway scenario	This scenario illustrated a potential set of policies employed by other states or countries that could be adopted to get Minnesota substantially closer to its GHG reduction goals.	2: Potential Policies Pathway before federal rollbacks 4: Potential Policies Pathway after federal rollbacks 5: Potential Policies Pathway after federal rollbacks, without a cap-and-invest policy
Net-Zero Pathway scenario	This scenario constrains the Potential Policies Pathway to achieve carbon neutrality by 2050 and interim goals through the least-cost path. It uses a calculated carbon price to change behavior to meet emissions goals, without specifying the policies that will achieve carbon neutrality.	6: Net-Zero Pathway with the Potential Policies Pathway after federal rollbacks

High-level descriptions and uses of the six modeled scenario variations are presented in Table 4. Specific policies for each core scenario are outlined under the GCAM and Agriculture and LULUCF modeling sections of this document. The constraints used in the Net-Zero Pathway scenario are listed in Table 8.

Table 4. Modeled scenario variation descriptions and analytical uses.

Scenario variation	Description	Use
1. Current Policies before federal rollbacks	Included current state and federal policies as they existed on January 1, 2025, prior to the federal policy rollbacks.	Allowed Current Policies scenario comparisons that showed the possible impact of federal policy changes.
2. Potential Policies Pathway before federal rollbacks	Included current state and federal policies as they existed on January 1, 2025, with additional potential state policies	Allowed Potential Policies Pathway scenario comparisons that showed the possible impact of federal policy changes.
3. Current Policies after federal rollbacks	Included current state and federal policies as they existed on July 31st, 2025, after the federal policy rollbacks, including proposed rule changes	Assessed the impacts of current state and federal policies after federal policy changes. Served as the baseline for Climate Action Framework analysis.
4. Potential Policies Pathway after federal rollbacks	Included current state and federal policies as they existed on July 31, 2025, including proposed rule changes, with additional state policies layered on top.	Assessed the impacts of a set of additional policies from the Climate Action Framework after federal policy changes. Served as the main policy alternative for Climate Action Framework analysis.
5. Potential Policies Pathway without a cap-and-invest policy after federal rollbacks	Included current state and federal policies as they existed on July 31, 2025, including proposed rule changes, with additional state policies layered on top as in Scenario 4; however, the cap-and-invest policy in the Potential Policies Pathway was excluded from this scenario variation.	Allowed for sensitivity analysis comparing the potential impacts of a cap-and-invest policy.
6. Net-Zero Pathway	Included current state and federal policies as they existed on July 31st, 2025, including proposed rule changes, with additional state policies layered on top as in Scenario 4; however, constraints were added to meet statewide and sectoral GHG emissions reduction goals. Because the agriculture and LULUCF sectors were not modeled within a cost-optimization framework, the results of the Potential Policies Pathway after federal rollbacks served as fixed inputs to the Net-Zero Pathway for those sectors.	A previous version of this scenario helped determine areas with high potential for effective intervention. Illustrated a pathway beyond the Potential Policies Pathway scenario to reach net zero, but did not identify the policies that would result in the necessary reductions

The scenarios used for comparison of the Current Policies and Potential Policies Pathway for the Climate Action Framework in this analysis are:

- Scenario 3: Current Policies after federal rollbacks
- Scenario 4: Potential Policies Pathway after federal rollbacks

The other scenarios help uncover specific insights, such as the impacts of federal rollbacks or the effects of a specific policy lever. Except when explicitly comparing the impacts of the federal rollbacks, the analysis will always refer to the variations of the scenarios after the federal rollbacks have been incorporated, and simplified scenario and variation names are used.

Scope and context

The scope of these analyses was limited to in-state emissions and sequestration, following the production-based accounting convention of state and national-scale GHG inventories set forth by the Intergovernmental Panel on Climate Change (IPCC).[2] This scope aligns with that of Minnesota's Greenhouse Gas Inventory,[3] which will be used to assess progress against statutory emissions-reduction requirements. In some cases, policy outcomes led to either increased or avoided emissions outside state borders (e.g., land management that reduces out-of-state synthetic nitrogen fertilizer production or the substitution of steel or cement with long-lived wood products). While impactful and potentially quantifiable, these out-of-state emissions changes are not accounted for in this analysis, though care was taken to avoid policies that would likely increase out-of-state upstream or downstream emissions.[4]

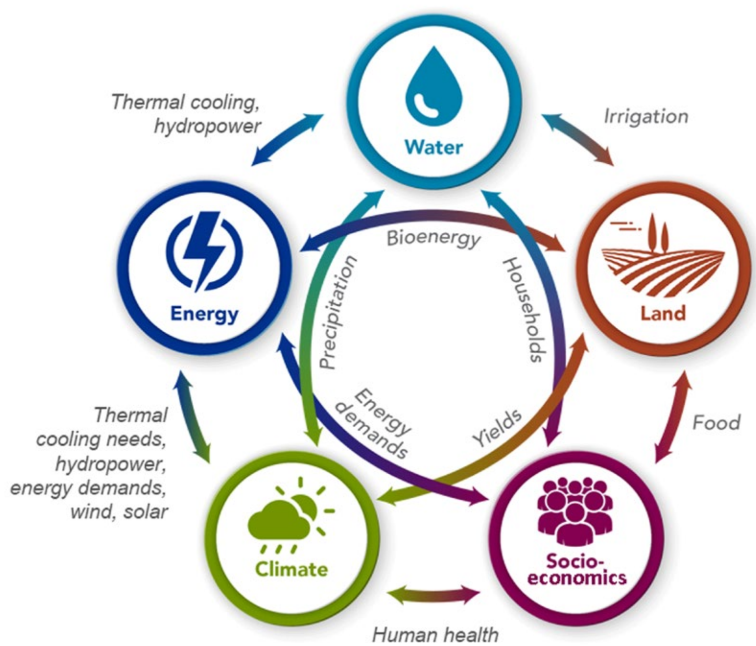
GHG emission forecast results were calibrated to the most recent historical Minnesota GHG emissions inventory. Global warming potentials (GWPs) with a 100-year time horizon, as reported in the IPCC's Fifth Assessment Report,[5] were used to convert non-carbon dioxide (CO_2) gases to CO_2 equivalents (CO_2-eq).

Global Change Analysis Model background

The Global Change Analysis Model (GCAM) is a sophisticated tool for assessing and projecting the impacts of policies and scenarios on greenhouse gas emissions and other environmental factors (Figure 7). It is used widely in climate and energy research, including the US National Climate Assessment, EPA Greenhouse Gas Emission Projections, IPCC Assessment Reports, IPCC Shared Socioeconomic Pathways, and in-state and regional research throughout the US.

GCAM is a dynamic-recursive, market-equilibrium, multisector, integrated assessment model developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute.[6] GCAM includes representations of the economy, energy, agriculture, and water supply for 32 global geopolitical regions, including the United States.

Figure 7. Linkages between water, land, energy, climate, and socioeconomic systems in GCAM.



This study used a US-focused version of GCAM, GCAM-USA, that disaggregates

[2] IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

[3] MPCA. 2025. Inventory of greenhouse gas emissions: 2005 to 2022. Available at: https://www.pca.state.mn.us/sites/default/files/lraq-3sy25.pdf

[4] For more information on out-of-state or consumption-based emissions in Minnesota, see Appendix C: Consumption-Based Emissions.

[5] IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

[6] JGCRI, 2023. GCAM Documentation. Available at: https://jgcri.github.io/gcam-doc/Joint Global Change Research Institute.

the United States and its economic components into the 50 states and the District of Columbia, while maintaining the original level of detail for the 31 regions comprising the rest of the world.

The energy system representation in GCAM-USA includes depletable primary sources of energy such as coal, gas, oil, and uranium, in addition to renewable resources such as bioenergy, hydropower, wind, and geothermal. GCAM-USA also describes the processes that transform these resources into final energy carriers, such as oil refining and electric power, that deliver services to end users in the buildings, transportation, and industrial sectors. The electric power sector includes various power generation technologies fueled by fossil fuels, renewables, bioenergy, and nuclear power.

GCAM-USA can model various policies addressing climate change and managing environmental impacts, including carbon pricing, emissions standards, fuel efficiency standards, renewable energy, energy efficiency technologies, carbon capture and storage, and other energy transition policies. The model uses regional population growth and labor productivity assumptions to guide how energy and land use are managed, including agriculture and forest products, and to test how new energy technologies and policies might impact GHG emissions. GCAM-USA can produce simulations from 1990 to 2100 in five-year increments and produce projections of future energy needs and climate effects for multiple GHGs and emissions of other air pollutants, including particulate matter, nitrogen oxides, non-methane volatile organic chemicals, sulfur dioxide, ammonia, and carbon monoxide.

As a market-equilibrium model, GCAM-USA balances supply and demand across markets by solving for market prices at which the quantity supplied equals the quantity demanded, depending on many inputs. Each five-year modeling period starts with the previous period's results and adds policy and other constraints to determine the new equilibrium prices and quantities. GCAM-USA tracks energy flows to ensure that the energy supply meets global and regional demand. It also tracks technologies and capital cost expenditures, such as for cars, buildings, and power plants, replacing old equipment and adding more when demand increases.

Compared to using a variety of sector-specific models, using GCAM-USA prioritizes consistency, integration, and breadth over the high resolution of narrowly focused, independent models. The results from this forecasting project may guide future analyses with additional models, which could provide additional perspectives helpful for policy development and implementation.

GCAM-USA has limited ability to assess the movement of GHGs between Earth's surface and atmosphere, and changes in carbon stored in natural materials like soil, trees, and plants (biogenic carbon stocks), at the spatial scale and boundaries of this analysis. Therefore, the MPCA conducted a parallel forecasting effort for the agriculture and LULUCF sectors. See the Agriculture and LULUCF modeling background section for details.

GCAM-USA-CGS

In this study, we used GCAM-USA-CGS, a version of GCAM-USA developed by the University of Maryland, Center for Global Sustainability research team, based on the open-source release of GCAM-USA 7.3.[7] The UMD-CGS research team has modified the GCAM-USA reference case data for many analysis projects to include the most up-to-date state and federal policies. To develop our modeled scenarios, UMD-CGS used an overall modeling approach consistent with previous analyses, including Maryland's Climate Pathway,[8]

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[7] Bond-Lamberty, B.; Pralit Patel; Lurz, J.; Pkyle; Kvcalvin; Smith, S.; Abigailsnyder; Dorheim, K. R.; Mbins; Link, R.; Skim301; Nealtg; Kanishka Narayan; Aaron, S.; Leyang Feng; Enlochner; Cwroney; Lynch, C.; Jhoring; Zarrar Khan; Siddarthd96; Orourkepr; JonathanHuster; Haewon; Waite, T.; Ou, Y.; Gokul Iyer; Mwisepnnl; Zhao, X.; Marideeweber. JGCRI/Gcam-Core: GCAM 7.0, 2023. Available at: https://doi.org/10.5281/ZENODO.8010145.

[8] Kennedy, K., A. Zhao, S. Smith, K. O'Keefe, B. Phelps, S. Kennedy, R. Cui, C. Dahl, S. Dodds, S. Edelstein, S. Francis, E. Ghosh, G. Hurtt, D. Irani, L. Ma, Y. Ou, R. Praisa, A. Taylor, A. Trivedi, N. Wetzler, J. Williams, and N. Hultman (2023). "Maryland's Climate Pathway: An analysis of actions the State can take to achieve Maryland's nation-leading greenhouse gas emissions reduction goals." Center for Global Sustainability, University of Maryland. Available at: https://www.marylandsclimatepathway.com/

Accelerating America's Pledge,[9] An All-In Climate Strategy Can Cut US Emissions by 50% by 2030,[10] Blueprint 2030,[11] and An All-In Pathway to 2030: The Beyond 50 Scenario.[12]

Some aspects of the model were customized for this analysis, such as separating residential energy consumption by income decile to enable targeted policy application for low-income groups. It was also calibrated to the latest non-CO_2 marginal abatement cost curves from the US Environmental Protection Agency.[13]

Air pollutant results from GCAM-USA-CGS were used to assess public health outcomes in the EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA).[14] Fuel consumption, fuel prices, and capital cost expenditure outputs were used to assess economic outcomes in the REMI PI+ model.[15]

Forecasting involves making many predictions about how the future will unfold in Minnesota. This study relies on a set of core assumptions about economic growth, population growth, the retirement of coal power plants, the relicensing of nuclear power plants, and the energy demands of our society. These core assumptions are documented in Appendix A: Core GCAM .

The scenarios were produced by changing parameters in GCAM-USA-CGS, either directly or based on information from bottom-up aggregation analysis. The modifications to create the Current Policies, Net-Zero Pathway, and Potential Policies Pathway scenarios are documented in Appendix B.

Calibration

Forecasted scenario results were calibrated to the historical Minnesota GHG Emission Inventory 2020 estimate, which is the most recent year for which historical data exists and overlaps with a model output year. After the UMD-CGS team completed their modeling, analytical summary, and documentation, revisions to the historical MPCA GHG emission inventory led to changes in estimated emissions, requiring recalibration of the forecasts to the historical data. Therefore, the results reported here differ slightly from those in the UMD-CGS report. The calibration enabled the analysis to align with the goals based on 2005 emissions and reflect the context of recent actions. The 2020 emissions were affected by the pandemic, and the anomaly was accounted for in the GCAM model and the data underlying the core assumptions. Recovery following the pandemic has led to an increase in emissions, which is accounted for in this model. However, because of the every-fifth-year forecasting increments, the graphics don't show year-to-year variation between each modeled year. Additional

[9] Hultman, N.; Frisch, C.; Clarke, L.; Kennedy, K.; Bodnar, P.; Hansel, P.; Cyrs, T.; Manion, M.; Edwards, M.; Lund, J.; Bowman, C.; Jaeger, J.; Cui, R.; Clapper, A.; Sen, A.; Saha, D.; Westphal, M.; Jaglom, W.; Altimirano, J. C.; Hashimoto, H.; Dennis, M.; Hammoud, K.; Henderson, C.; Zwicker, G.; Ryan, M.; O'Neill, J.; Goldfield, E. Accelerating America's Pledge: Technical Appendix; Bloomberg Philanthropies with University of Maryland Center for Global Sustainability, Rocky Mountain Institute, and World Resources Institute: New York, 2019. Available at: https://www.americaisallin.com/sites/default/files/2022-09/technical-appendixaccelerating-americas-pledge.pdf

[10] Hultman, N. E.; Clarke, L.; Frisch, C.; Kennedy, K.; McJeon, H.; Cyrs, T.; Hansel, P.; Bodnar, P.; Manion, M.; Edwards, M. R.; Cui, R.; Bowman, C.; Lund, J.; Westphal, M. I.; Clapper, A.; Jaeger, J.; Sen, A.; Lou, J.; Saha, D.; Jaglom, W.; Calhoun, K.; Igusky, K.; deWeese, J.; Hammoud, K.; Altimirano, J. C.; Dennis, M.; Henderson, C.; Zwicker, G.; O'Neill, J. Fusing Subnational with National Climate Action Is Central to Decarbonization: The Case of the United States. Nat. Commun. 2020, 11 (1), 5255. Available at: https://doi.org/10.1038/s41467-020-18903-w.

[11] Kennedy, K.; Jaglom, W.; Hultman, N.; Bridgwater, R.; Mendell, H.; Leslie-Bole, H.; Rowland, L.; McGlynn, E.; Massey-Green, T.; Cyrs, T.; Clarke, L.; McJeon, H.; Zhao, A.; O'Neill, J.; Gasper, R.; Feldmann, J.; O'Keefe, K.; Cui, R.; Kennedy, S.; Zhao, J.; Kazanecki. Stronger Together: An All-In Climate Strategy for Faster, More Durable Emissions Reductions; America Is All In, 2021.Available at: https://www.americaisallin.com/blueprint-2030

[12] Zhao, A.; Kennedy, S.; O'Keefe, K.; Borrero, M.; Clark-Sutton, K.; Cui, R.; Dahl, C.; Deye, G.; Feldmann, J.; Kennedy, K.; McJeon, H.; Moravec, M.; Nilov, D.; Rajpurohit, S.; Rosas, J.; Squire, C.; Hultman, N. An All-In Pathway To 2030: The Beyond 50 Scenario; Center for Global Sustainability and America is All In, 2022; p 16. Available at: https://cgs.umd.edu/sites/default/files/2022-11/All%20In-The%20Beyond%2050%20Scenar io-Report-Nov%202022.pdf

[13] United States Environmental Protection Agency. Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015-2050; EPA-430-R-19-010; United States Environmental Protection Agency, Office of Atmospheric Programs: Washington, DC, 2019. Available at: https://www.epa.gov/sites/default/files/2019-09/documents/epa_non-co2_greenhouse_gas es_rpt-epa430r19010.pdf.

[14] CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA). Available at: https://www.epa.gov/cobra (accessed 2023-03-15).

[15] REMI Available at: https://www.remi.com/model/pi/

forecasts can be made in the future using updated input data and can be calibrated to the 2025 historical inventory when available.

GCAM-USA-CGS modeling scenario descriptions

Versions of the Current Policies and Potential Policies Pathway scenarios were initially developed to represent the state of federal policy as of January 1, 2025. Numerous changes to federal policy have been made and proposed since then, necessitating revisions to the modeling scenarios to better reflect the current landscape as of July 31, 2025.[16] The following sections describe the variations of the scenarios before and after the federal policy rollbacks. A conservative approach was taken to assume the complete rollback of policies that are proposed, under litigation, or are otherwise uncertain to be maintained. A comparison of the scenarios before and after the federal rollbacks provides a range for forecasts, given the uncertainty of federal developments.

Current Policies scenario

The Current Policies scenario modeled existing policies in Minnesota, as well as relevant federal policy, initially including many of the climate-related provisions from the Bipartisan Infrastructure Law (BIL), American Innovation and Manufacturing (AIM) Act, and the Inflation Reduction Act (IRA). The IRA provisions included in the forecast, along with their status in the scenario variations after federal rollbacks and proposed rescissions, are shown in Table 5.[17] A conservative approach was used, assuming that proposed changes would be implemented. Model parameters representing the policies are detailed in Appendix B.

Current policies in Minnesota were defined as on-the-books policies, including those to be implemented under legislative mandates (Table 6 and Appendix B). This scenario excludes targets without implementation mechanisms, such as the greenhouse gas emission-reduction goals.

The Clean Electricity Standard[18] (CES) was modeled by retiring fossil fuel generation units based on public plans and constraining new construction to meet the standards and capacity necessary to meet projected electricity demand.[19] The CES may be achieved through renewable energy credits (RECs) and carbon capture and sequestration (CCS); imported electricity was assumed to meet the remaining percentage of clean electricity not generated within the state. Following the assumptions made in the Midwest Independent System Operator (MISO) regional planning,[20] nuclear power facilities were modeled as if they would receive further relicensing.[21] The Renewable Electricity Standard[22] was modeled by requiring utilities to generate or purchase electricity that meets the standard's eligible technology criteria.

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[16] Stein, Sophia, Claire Squire, and Alicia Zhao. (2025) A Review of Federal Climate Policy Rollbacks in the United States: Trends, Sectoral Changes, and Implications for Policymakers. University of Maryland School of Public Policy, Center for Global Sustainability. Available at: https://cgs.umd.edu/research-impact/publications/review-federal-climate-policy-rollbacks-united-states-trends-sectoral

[17] Ibid.

[18] Minn. Stat. 216B.1691 Available at: https://www.revisor.mn.gov/statutes/cite/216B.1691

[19] MN Dept. of Commerce. 2021. Energy Policy and Conservation Quadrennial Report, 2020. Available at: https://mn.gov/commerce-stat/pdfs/20210301_quad_report.pdf

[20] MISO Futures Report Series 1A. 2023. Available at: https://cdn.misoenergy.org/Series1A_Futures_Report630735.pdf

[21] Xcel plans to extend Monticello through 2040, and plans request to extend Prairie Island reactors through 2043 and 2044.

[22] Minn. Stat. 216B.1691 Available at: https://www.revisor.mn.gov/statutes/cite/216B.1691

Table 5. Modeled Inflation Reduction Act (IRA) and other federal or state policies with model status after federal rollbacks.

Sector	Policy	Status after federal rollbacks
Electricity - IRA	Section 13101 – Production tax credit (PTC) extension	Rolled back
	Section 13102 – Investment tax credit (ITC) extension	Rolled back
	Section 13015 – PTC for existing nuclear	Maintained
	Section 13302 – Residential clean energy credit	Rolled back
	Section 13701 – New clean electricity PTC	Rolled back
	Section 13702 – New clean electricity ITC	Rolled back
	Section 50144 – Energy Community Reinvestment Financing	Maintained
	Section 13104 – 45Q: extension of credits for captured CO_2	Maintained
Transportation - IRA	Sections 13201/13202 – Extension of incentives for biofuels	Maintained and extended
	Section 13203 – Sustainable aviation biofuels	Maintained
	Section 13401 – Clean vehicle credit	Rolled back
	Section 13403 – Commercial clean vehicle credit	Rolled back
	Section 13404 – Alternative refueling property credit	Rolled back
	Section 13704 – Clean fuel PTC	Maintained and extended
Buildings - IRA	Section 13301 – Energy-efficient home improvement credit	Rolled back
	Section 13303 – Energy-efficient commercial building deduction	Rolled back
	Section 13304 – Energy-efficient home credit	Rolled back
	Section 50121 – Home energy efficiency credit	Rolled back
	Section 50122 – High-efficiency home rebate program	Proposed rescission
Industry and other - IRA	Section 13204 – 45V: production credits for clean hydrogen	Rolled back
	Section 60113 – Methane Emissions Reduction Program	Rolled back
Other federal policies	Corporate Average Fuel Economy Standards[23]	Proposed rescission
	EPA Power Plant regulations: New natural gas plant efficiency standards and 90% carbon capture from existing coal- and natural gas-fired plants[24]	Proposed rescission
Policies in other states	Advanced Clean Cars II and Advanced Clean Trucks	Proposed rescission
	Renewable Portfolio Standards	Maintained

[23] National Highway Traffic Safety Administration. Corporate Average Fuel Economy. Available at: https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy

[24] EPA. GHG Standards and Guidelines for Fossil Fuel-Fired Power Plants. Available at: https://www.epa.gov/stationary-sources-air-pollution/greenhouse-gas-standards-and-guidelines-fossil-fuel-fired-power

Table 6. Modeled current Minnesota policies and assumptions.

Sector	Policy	Target
Electricity	Clean Electricity Standard[25]	By 2030: 80% carbon-free for public utilities, 60% for other utilities
		By 2035: 90% carbon-free, all utilities
		By 2040: 100% carbon-free electricity, all utilities
	Renewable Electricity Standard[26]	By 2025: 25% of retail electricity sold is from renewable resources (for Xcel - 30% by 2020)
		By 2035: 55% of retail electricity sold is from renewable resources
	Planned retirements	All proposed coal unit retirements in the state follow the schedule in the Quadrennial Report.[27]
	Nuclear relicensing[28]	Assume continuous relicensing through 2050.
Transportation	Sustainable aviation fuel (SAF)	Apply a refundable tax credit of $1.50 per gallon of SAF produced or blended in Minnesota for fuel for aircraft departing a Minnesota airport, reducing lifecycle GHGs by at least 50%.
Buildings	Building code[29]	New construction meets the most recent American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards.
Agriculture	Climate Smart Food Systems	Conservation agriculture and soil health programs funded by state and federal programs; Peatland restoration on existing croplands; Existing and planned biochar production facilities. These policies were modeled outside of GCAM-USA; see the Agriculture and LULUCF Modeling Scenarios section for details.
Land use, land-use change, and forestry	Climate Smart Food Systems	Peatland restoration on partially drained peatlands and fully drained grasslands. These policies were modeled outside of GCAM-USA; see the Agriculture and LULUCF Modeling Scenarios section for details.

[25] Minn. Stat. 216B.1691 Available at: https://www.revisor.mn.gov/statutes/cite/216B.1691

[26] Ibid.

[27] MN Dept. of Commerce. 2021. Energy Policy and Conservation Quadrennial Report, 2020. Available at: https://mn.gov/commerce-stat/pdfs/20210301_quad_report.pdf

[28] MISO Futures Report Series 1A. 2023. Available at: https://cdn.misoenergy.org/Series1A_Futures_Report630735.pdf

[29] Minn. Stat 326B.106, Subd. 1 (e) Available at: https://www.revisor.mn.gov/statutes/cite/326B.106

Potential Policies Pathway scenario

The Potential Policies Pathway (PPP) scenario modeled several potential state-level policies in addition to the current policies. The Current Policies scenario variations served as the basis for the Potential Policies Pathway scenarios, which also have variations forecasted before and after federal rollbacks. Potential policies are listed in Table 7 and described below. Model parameters are described in detail in Appendix B.

Table 7. Minnesota-specific policies modeled in GCAM-USA-CGS in the Potential Policies Pathway scenario variations.

Sector	Measure	Potential policies
Transportation	Increase travel options and reduce passenger vehicle use	**Vehicle miles traveled reduction policy** – Adopt policies supportive of achieving a 20% reduction in passenger vehicle miles traveled per capita by 2050, compared to 2019.
	Reduce the carbon intensity of transportation energy	**Electric passenger vehicles** – Adopt policies that support higher rates of new electric passenger cars, trucks, and SUVs. **Electric truck adoption** – Adopt policies that support higher rates of new electric medium- and heavy-duty vehicles. **Clean transportation standard** – Adopt regulatory standards requiring transportation fuel suppliers to meet the petroleum replacement goal of 25% biofuel use in gas by 2030 and reduce the carbon intensity of fuels by 25% by 2030, 75% by 2040, and 100% by 2050, compared to 2018 levels.
Commercial and residential buildings	Improve building efficiency	**Building efficiency standards** – Fully implement efficiency standards in the current building code: by 2036, require an 80% reduction in energy consumption in new commercial construction, compared to 2004 standards, and by 2038, require a 70% reduction in energy consumption in new residential construction, compared to 2006 energy use. **Energy efficiency resource standards** – Revise the energy-savings goals for residential and commercial natural gas customers. **Building retrofitting** – 1) Benchmark and implement an energy management plan for commercial buildings over 25,000 ft^2 and achieve 50% of new construction efficiency standards for buildings over 50,000 ft^2; 2) Weatherize income-eligible homes within 10 years.
Industrial	Provide market incentives for cost-effective mitigation	**Cap-and-invest for large industrial emitters** – Adopt a cap-and-invest or fee-and-dividend program; starting in 2028, phase in the cap with a 45% reduction at 10 years, 70% reduction at 17 years, and 95% at 27 years.
	Explore efficiency, electrification, and alternative energy	**Industrial energy efficiency standards** – Revise energy-savings goals for industrial natural gas customers; incentivize implementation of ISO 50001 energy management systems and certification.
Waste	Reduce methane emissions from waste	**Anaerobic digestion** – Incentivize anaerobic digestion at wastewater treatment plants, with possible co-digestion of food waste and other organic materials. **Landfill gas capture** – Establish limits for GHG emissions and require the implementation of collecting and treating landfill gas.
	Divert and redirect waste	**Recycling and solid waste management –** Implement a beverage container deposit refund program. Extend the metro area recycling rate statewide. Implement recommendations in the MPCA Sustainable Materials Management and Solid Waste Policy Report.[30]

[30] These polices could not be modeled within GCAM. Emission reductions were estimated from waste sector policy recommendations.

Sector	Measure	Potential policies
Agriculture *See the Agriculture and LULCUF Modeling Scenarios section for details.*	Sequester carbon and reduce GHG emissions from agricultural lands	**Climate-smart agricultural practices** – Implement climate-smart agricultural practices (no-till, cover crops, perennial crops, perennial borders) on 80% of Minnesota's 21 million cropland acres.
	Reduce nitrogen losses from croplands	**Enhanced efficiency fertilizers** – Transition 100% of synthetic nitrogen fertilizers to slow- or controlled-release versions by 2050.
	Reduce GHG emissions from manure management and enteric fermentation	**Manure management** – Implement practices or technologies to reduce GHG emissions from manure management at most feedlots by 2050. Techniques could include solid-liquid separation, covering and flaring, anaerobic digestion, and reduced crude protein in swine and beef diets. **Feed additives** – Reduce enteric emissions with feed additives on 50% of confinement-fed cattle.
Land use, land-use change, and forestry (LULUCF) *See the Agriculture and LULCUF Modeling Scenarios section for details.*	Sequester more carbon in landscapes and products	**Expanded forest cover** – Achieve a tenfold increase in the annual rate of tree planting in historically forested regions of the state. **Biochar** – Increase production and land application of biochar tenfold by 2050. **Long-lived harvested wood products** – Double the production and use of long-lived harvested wood products by 2050.
	Prevent loss of sequestered carbon in landscapes	**Avoided forest conversion** – Achieve a 50% reduction in annual permanent forest conversion to development and agriculture. **Peatland restoration** – Restore 50% of degraded peatlands by 2050.

Clean transportation standard

A clean transportation standard (CTS) gradually lowers the carbon intensity of transportation fuels. This fuel-neutral policy encompasses GHG emissions throughout the fuel lifecycle, including extraction or production through delivery and use in vehicles. The model was constrained to:

- Match regulatory standards that require transportation fuel suppliers to meet the petroleum replacement goal of 25% biofuel use in gasoline by 2030, aligning with the recommendations from the Governor's Council on Biofuels.[31]
- Represent regulatory standards that would require transportation fuel suppliers to reduce the carbon intensity of fuels by 25% by 2030, 75% by 2040, and 100% by 2050 (compared to 2018 levels).

The CTS workgroup modeling results[32] demonstrated that the carbon intensity targets included in the law may be challenging to achieve. Because the Climate Action Framework attempted to identify ambitious and transformative policies, and the transportation sector has overall GHG reduction goals, it was decided that the modeling would use the full CTS, rather than reduced goals.

Increased travel options and reduced passenger vehicle use

Passenger vehicle mileage projections were modeled to represent the impact of a portfolio of policies from the Statewide Multimodal Transportation Plan that would increase transportation options and decrease passenger vehicle miles traveled (VMT). The model constrained the growth of transportation services to reduce passenger vehicle per capita VMT from 10,691 miles in 2019 by 4% by 2025, 8% by 2030, 11% by 2035, and

[31] Report in fulfillment of Executive Order 19-35 establishing the Governor's Council on Biofuels. November 2, 2020. Available at: https://www.mda.state.mn.us/sites/default/files/docs/2020-11/GovernorsCouncilBiofuelsReport_ExecOrder19-35.pdf

[32] MN DOT. Clean Transportation Fuel Standard Working Group. Available at: https://www.dot.state.mn.us/sustainability/clean-transportation-fuel-standard-working-group.html

14% by 2040.[33] In 2023, Minnesotans averaged 10,140 passenger VMT per capita, which is below the 2025 goal.[34]

Individual policies, such as active transportation investments, could not be forecasted in the GCAM model used for this project because they were too narrowly focused for the model inputs. Instead, the outcomes of these policies were collectively represented by the overall reduction in VMT that they were designed to achieve together.

Advancing the transition to zero-emissions vehicles

The model was set up to represent accelerating the transition to electric vehicles (EVs) or zero-emission vehicles (ZEVs), the expansion of the charging infrastructure, and support of light-, medium-, and heavy-duty EV adoption, as well as the adoption of electric off-road vehicles, engines, and other equipment. The model parameters were constrained by the assumption that new passenger vehicle sales would reach 100% EV/ZEV by 2035, and that new medium- and heavy-duty vehicle sales would reach 40-75% EV/ZEV by 2035, depending on vehicle class. However, the viability of this policy was affected by federal rollbacks and was not applied in the PPP scenario.

Residential and commercial natural gas efficiency resource standards

The model parameters included increasing the current energy-savings goals[35] from 1.75% (adjustable down to 1%) to 2% annual energy savings for aggregated residential and aggregated commercial natural gas customers beginning in 2030.

Building code efficiency standards

The model included full implementation and compliance with current and future commercial and residential energy codes.

The commercial code efficiency standards specify that beginning in 2024, model commercial energy codes will be updated with each new published edition of ASHRAE 90.1 or a more efficient standard.[36] By 2036, the energy code for new commercial buildings must reduce energy consumption by 80% compared to the 2004 code.[37]

The residential code efficiency standards specify that beginning in 2026, model residential energy codes will be updated with each new published edition of the International Energy Conservation Code or a more efficient standard.[38] By 2038, the energy code for new residential buildings must reduce energy consumption by 70%, compared to the 2006 International Energy Conservation Code State Level Residential Codes Energy Use Index for Minnesota, as published by the United States Department of Energy's Building Energy Codes Program.[39]

In addition, the model included the parameter that by 2035, commercial building retrofitting must achieve a reduction in energy consumption equal to 50% of the new-construction building code energy reductions.

Residential weatherization and electrification

The model included weatherization and electrification, within 10 years, for all income-eligible households, modeled at 80% of the Minnesota median household income, or approximately 450,625 eligible homes.

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[33] Statewide Multimodal Transportation Plan (SMTP)

[34] Annual vehicle miles traveled by the average Minnesotan. Available at: https://www.dot.state.mn.us/measures/vehicle-miles-traveled.html

[35] Minn. Stat 216B.241, Subd. 1 (c). Available at: https://www.revisor.mn.gov/statutes/cite/216B.241#stat.216B.241.1c

[36] Minn. Stat 326B.106, Subd. 1 (e) Available at: https://www.revisor.mn.gov/statutes/cite/326B.106

[37] Ibid.

[38] Minn. Stat 326B.106, Subd. 1 (g) Available at: https://www.revisor.mn.gov/statutes/cite/326B.106

[39] Ibid.

Industrial natural gas energy efficiency standards

The model included an increase to the current energy-savings goals[40] from 1.75% to 3% annual energy savings for industrial natural gas customers, starting in 2030. An energy efficiency resource standard (EERS) establishes energy efficiency targets requiring energy savings or reductions during peak demand. Minnesota also credits load management toward energy efficiency targets when integrated into efficiency programs.

Smaller facilities, such as those emitting less than 25,000 metric tons of carbon dioxide equivalent ($MTCO_2$-eq) or more annually, would also be eligible for assistance to meet an efficiency standard. This could include technical assistance, incentivized implementation of ISO 50001[41] energy management systems, and certification for site-level or organization-level energy efficiency improvements.

Cap-and-invest for large emitters

The model was modified to include a market-based cap-and-invest program for permitted sources of GHG emissions that emit 25,000 $MTCO_2$-eq or more annually, excluding electric utilities and the iron ore mining and processing industry. The program was modeled after the structure and schedule of a cap-and-invest program adopted by the state of Washington, which phased in capped emission reductions to achieve a 45% reduction in 10 years, a 70% reduction in 17 years, and a 95% reduction in 27 years.[42] The hypothetical cap was set at 10% of Minnesota's total forecasted GHG emissions in 2025, approximately the share of GHG emissions from the facilities included in this design relative to statewide emissions. Phasing in the cap would mean that, 10 years after beginning the program, the allowable emissions for covered facilities would be 45% of 10% of 2025 emissions, and would continue in the same fashion for the following milestones.

The cap value of 10% of 2025 emissions was derived from MPCA air emissions point-source facility data from 2021 to 2023, during which 69 to 72 Minnesota facilities exceeded the 25,000 $MTCO_2$-eq threshold in any single year and were not otherwise exempted from a hypothetical cap-and-invest program.[43] In 2021, 69 cap-eligible facilities emitted 9.3% of state net GHG emissions; in 2022, 69 cap-eligible facilities emitted 9.5% of state net GHG emissions; and in 2023, 72 cap-eligible facilities emitted 9.6% of state net GHG emissions.[44] This group of sources accounts for an increasing share of Minnesota’s total GHG emissions because industrial sources have been slower to reduce emissions than other sectors.

Electric utilities were exempted because they are covered by the Clean Electricity Standard. Taconite production was exempted because investments to decarbonize the entire steel manufacturing process may be more efficient and effective if applied to other steps in production that occur in different states. Under the modeled cap-and-invest policy, covered entities and voluntary participants could choose their most cost-effective strategies, including purchasing allowances at auctions or from other entities, obtaining allowances through no-cost allocation, earning or purchasing offset credits, and reducing greenhouse gas emissions. Industries not covered by the cap could also participate and sell qualifying credits. Allowances could be used for compliance, saved for use in a future year, or traded between market participants. In addition, covered industrial manufacturing entities could be allocated no-cost allowances on a reduction schedule that supports transition and emission reductions while maintaining operations and competitiveness and reducing the likelihood of unintentionally displacing emissions beyond Minnesota’s borders.

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[40] Minn. Stat 216B.241 Subd. 1 (c) https://www.revisor.mn.gov/statutes/cite/216B.241#stat.216B.241.1c

[41] ISO 50001. Available at: https://www.iso.org/iso-50001-energy-management.html

[42] State of Washington, Department of Ecology. Washington’s Cap-and-invest Program. Available at: https://ecology.wa.gov/air-climate/climate-commitment-act/cap-and-invest

[43] MPCA air emissions point source facility data https://data.pca.state.mn.us/#/views/Airemissions-pointsourcefacilitydata/Byfacility?:iid=1

[44] Ibid.

The model prioritized the least-cost reductions in emissions, emulating allowance trading, and was constrained to limit annual cost increases to the Washington policy price-ceiling increase rate of 5%, plus an assumed 2% inflation rate per year.

Waste

Landfill emissions were assumed to decrease by about 50% from 2020 levels by 2050. This assumption includes technology deployment and strategies that reduce landfill methane emissions. Additionally, Minnesota municipal landfill data were used with the EPA LandGEM tool to calculate landfill methane generation and methane collection efficiencies, averaged across 2010-2023. The average collection efficiency was 48% for landfills with gas collection and control systems.

Net-Zero Pathway scenario

The Net-Zero Pathway scenario illustrates a pathway that meets our statewide and sectoral goals. This scenario is built on the Potential Policies Pathway scenario after federal rollbacks, with additional constraints that reflect Minnesota's statewide statutory emission-reduction goals (Table 8).

Table 8. Minnesota's Net-Zero Pathway constraints.

Type of prescribed goal	Scope of goal	Base year	Target year	Goal
GHG target	Statewide, economy-wide	2005	2025	30% reduction, net
			2030	50% reduction, net
			2050	Net-zero GHG emissions

Agriculture and LULUCF modeling background

Greenhouse gas emissions and sequestration from the agriculture sector and land use, land-use change, and forestry (LULUCF) sector are largely driven by biological processes such as plant growth and microbial respiration, rather than fuel combustion. For example, some of the largest GHG fluxes from these sectors in Minnesota include carbon sequestration in forests, soil carbon losses from drained wetlands, nitrous oxide emissions from agricultural soils, and methane emissions from cattle digestion.

GHG fluxes from these sectors were modeled by pairing anticipated baseline emissions with expected changes in emissions due to specific policies and actions. Baseline emissions trajectories in the absence of any recently enacted policies were determined using historical emissions and existing forecasts based on anticipated market-driven changes in Minnesota's agriculture and land use patterns. Changes in net emissions caused by specific policy outcomes were estimated using a variety of peer-reviewed emissions factors associated with changes to the practices utilized in crop agriculture, animal agriculture, and the management of forests and other lands and waters. Emissions factors are spatially- and temporally specified rates of emissions associated with a specific practice, activity, or type of management. These values are derived from observational research and models. Within agriculture and land use, land use-change, and forestry, the rate is typically expressed as metrics tons of a specific gas per acre per year. Emissions change factors are similar but are used to indicate the expected difference in emissions due a change in management for a given timeframe and unit of area. These expected changes in net GHG emissions were then summed with the baseline emissions to determine the expected net emissions by year and emissions or sequestration source or sink.

Where estimates of current activities and the potential feasibility of altered practices and technologies were necessary, we relied on the expert opinion of members of Minnesota's Interagency Natural and Working Lands goal team, with representation from the Minnesota Department of Natural Resources, Minnesota Department of Agriculture, Minnesota Board of Water and Soil Resources, and Minnesota Pollution Control Agency.

Agriculture and LULUCF modeling scenario descriptions

Agriculture and LULUCF emissions were modeled under the same core scenarios as the other economic sectors, with two exceptions, detailed below.

The agriculture and LULUCF modeling included the following scenarios:

- The Current Policies scenario before federal rollbacks reflects federal and state policies as of January 1, 2025.
- The Current Policies scenario after federal rollbacks is identical to the Current Policies scenario before rollbacks, except that it includes a hypothetical phaseout of the USDA Conservation Reserve Program. There are no known federal policy changes from the 2025 Reconciliation Bill expected to impact emissions from these sectors directly.
- The Potential Policies Pathway scenario before federal rollbacks includes eight policies or actions that span crop and animal agriculture, forestry and forest products, and restoration of natural lands. These policies were applied in addition to those in the Current Policies scenario. They were informed and generated by staff and leadership from the Minnesota Department of Natural Resources, Minnesota Department of Agriculture, Minnesota Board of Water and Soil Resources, and Minnesota Pollution Control Agency.
- The Potential Policies Pathway scenario after federal rollbacks expands analysis of the Potential Policies Pathway to include the hypothetical phaseout of the USDA Conservation Reserve Program.
- The Potential Policies Pathway scenario after federal rollbacks and without cap-and-invest is identical to the Potential Policies Pathway scenario after federal rollbacks for the agriculture and LULUCF sectors. This is because the hypothetical cap-and-invest policy would not directly regulate activities within these sectors.
- The Net-Zero Pathway scenario is identical to the Potential Policies Pathway scenario after federal rollbacks for the agriculture and LULUCF sectors. The agriculture and LULUCF modeling was not conducted within a dynamic-recursive market-equilibrium model, so it was not possible to assess the least-cost emissions reduction outcome for these sectors.

Baseline emissions

To assess the relative impact of the Current Policies and Potential Policies Pathway scenarios on net emissions from the agriculture and LULUCF sectors, we first generated a set of anticipated baseline emissions. These anticipated baseline emissions were largely based on the continuation of average emissions from recent years and expectations about economic growth, efficiency of agricultural operations, and ecological trajectories of natural lands. Baseline emissions do not account for any recently funded or expanded programs and reflect expected emissions in the absence of the relatively new policies included in the Current Policies scenario. We then summed expected changes in emissions due to the Current Policies and Potential Policies Pathway scenarios with these baseline emissions to determine expected net emissions from the agriculture and LULUCF sectors in each of the scenarios.

Agriculture baseline emissions expectations

To establish baselines for the agriculture sector, historical Minnesota GHG emissions[45] were paired with subsector-specific anticipated percent changes by 2050, derived from a Pathways Analysis conducted by Energy and Environmental Economics, Inc. (E3), published in 2022.[46]

Enteric fermentation

Annual emissions are expected to rise by 5.2% over the 2020-2022 average by 2050, due to increased global demand for dairy products under a business-as-usual scenario.

Manure management

Annual emissions are expected to increase by 4.9% for methane (CH_4) and 5.5% for nitrous oxide (N_2O) over the 2020-2022 averages due to rising global demand for animal products, tempered by increased adoption of improved manure management practices.

Cropland soils

E3's Pathways Analysis projected, but did not disaggregate, expected carbon stock changes within the LULUCF sector, which typically includes soil carbon in croplands. Therefore, we assumed that under a business-as-usual pathway without current policies, soil carbon stock changes in mineral and organic soils would continue at the average rates observed over the past ten years.

Nitrous oxide from agricultural soil management

Annual N_2O emissions from agricultural soil management are expected to decrease by 1.4% compared to the 2020-2022 average due to expectations of improved nitrogen management.

All other subsectors

CO_2 emissions from carbon-containing fertilizers, field burning of agricultural residues, rice cultivation, and land conversion to cropland are expected to remain at levels equal to the 2013-2022 average.

LULUCF baseline emissions expectations

To establish baselines for the LULUCF sector, historical GHG emissions were paired with results from separate analyses of in-forest and harvested wood products carbon fluxes,[47] as well as peatland GHG fluxes.[48] These two topic areas expand the scope of Minnesota's GHG inventory, so the methods from each were used to determine historical and projected baseline emissions for harvested wood products and specific types of peatlands, respectively.

Forests

A decrease in carbon sink strength due to aging forests is expected for the business-as-usual scenario from a recent study commissioned by the Minnesota Forest Resources Council.[49] One modification implemented with the approval and assistance of the original authors was the use of a polynomial linear model as a smoothing

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[45] MPCA. 2025. Greenhouse gas emissions in Minnesota 2005-2022: Biennial inventory report tracking the state's greenhouse gas emissions contributing to climate change. https://www.pca.state.mn.us/sites/default/files/lraq-3sy25.pdf

[46] E3 State-level PATHWAYS Analysis for US Climate Alliance member states, conducted in 2022. Available to US Climate Alliance member states, with summary available within the US Climate Alliance 2023 Annual Report: https://usclimatealliance.org/wp-content/uploads/2023/12/USClimateAlliance_AnnualReport_2023.pdf

[47] Zobel, J., Russel, M., Puettmann, M., Oneil, E., Wilson, D., Gifford, T., Du Plississ, J., Windmuller-Campione, M., Edgar, C., Sagor, E., Sahoo, K., Bjarvin, C. 2025. Estimating current and future carbon stocks and emissions in Minnesota forests and forest products under multiple management scenarios. Prepared for Minnesota Forest Resources Council.

[48] Hanson, P.J., Griffiths, N.A., Iversen, C.M., Norby, R.J., Sebestyen, S.D., Phillips, J.R., Chanton, J.P., Kolka, R.K., Malhotra, A., Oleheiser, K.C. and Warren, J.M., 2020. Rapid net carbon loss from a whole-ecosystem warmed peatland. *Agu Advances*, *1*(3), p.e2020AV000163.

[49] Zobel, et al. Estimating current and future carbon stocks and emissions in Minnesota forests and forest products under multiple management scenarios. (n 47)

function applied to the raw model outputs of net in-forest carbon flux. This served to minimize uninformative interannual variability that arose as an unintended consequence of the model-tuning process.

A continuation of the average flux from lands converted to forests during 2013-2022 from Minnesota's GHG Inventory was applied to 2023-2050. However, because Zobel *et al.*[50] included all existing forest (not only forest remaining forest), fluxes from new lands converted to forest were included by adding in 1/20th of the average flux from lands converted to forests per year during 2013-2022 starting in 2023 and continuing until 2042, at which point, it was held constant at 100% of the average flux from 2013-2022. Minnesota's GHG accounting framework separates forests remaining forests from lands converted to forests within the last 20 years, while Zobel *et al.*'s analysis combines all forests regardless of time since conversion. Phasing in the flux from lands converted to forest over 20 years allows the combination of Zobel *et al.*'s approach with Minnesota's GHG accounting framework, assuming that average fluxes from lands converted to forests will continue until at least 2050.

Forest fire non-CO_2 emissions were held at the average of those from 2004 to 2022 to include a more complete sampling of the range of possible annual emissions given the non-normal distribution of fire emissions and the availability of relevant wildfire-related data from the USDA Forest Service's Forest Inventory and Analysis (FIA) beginning in 2004.

Harvested wood products

We worked with authors of the Zobel *et al.* 2025 study to leverage their findings for harvested wood products (HWP) carbon pools under a business-as-usual scenario in Minnesota. They used a production approach to HWP accounting and anticipated decreased sink strength from HWP due to growth in inherited emissions from wood products currently in service or in solid waste disposal sites, paired with little change to the total production of long-lived wood products in Minnesota.

Wetlands: Intact peatlands

Historically, intact peatlands have been a long-term net GHG sink, but warming and altered precipitation patterns are generating elevated levels of methane emissions from global wetlands, and this trend is expected to continue.[51, 52] Data collected as part of The SPRUCE Experiment at Marcell Experimental Station were utilized to derive a linear relationship between annual average temperature and carbon flux for ombrotrophic bogs,[53] represented by the following equation:

$$\text{Carbon emitted (g/m}^2\text{)} = \text{Temperature (}^\circ\text{C)} \times 28.4 - 103$$

We conservatively applied the temperature-carbon relationship only to the acreage of histosols (soils that formed under waterlogged conditions and have high organic matter content) within wetland categories that match those of the SPRUCE Experiment site. Specifically, this was where the hydrogeomorphic description is terrene peatland vertical and the Simplified Plant Community Classification is either coniferous bog, open bog, or shrub wetland (per the Minnesota Department of Natural Resources' (DNR) Potentially Wet Histosols resource, accessed via Minnesota Geospatial Commons[54]). For polygons that met these criteria, we multiplied

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[50] Ibid.

[51] McFarlane, K.J., Hanson, P.J., Iversen, C.M., Phillips, J.R. and Brice, D.J., 2018. Local spatial heterogeneity of Holocene carbon accumulation throughout the peat profile of an ombrotrophic Northern Minnesota bog. *Radiocarbon*, *60*(3), pp.941-962.

[52] MPCA. 2022. "Greenhouse gas reduction potential of agricultural best management practices (Revised edition)" https://www.pca.state.mn.us/sites/default/files/p-gen4-21.pdf

[53] Hanson, P.J., et al., 2020. Rapid net carbon loss from a whole-ecosystem warmed peatland. (n 48).

[54] Minnesota Department of Natural Resources, Minnesota Geospatial Commons. Potentially Wet Histosols. https://gisdata.mn.gov/dataset/geos-potentially-wet-histosols

the percent histosol by the polygon area to determine the total histosol area, which totaled 2,352,683 acres, representing 90% of the total area of the polygons.

Historical (1990-2024) annual average temperature data were derived from the Minnesota DNR Climate Explorer[55] for the North Central and Northeast climate divisions. Projected annual average temperature data under an intermediate emissions scenario (SSP 245) were taken from the MN CliMAT Tool[56] for a similar area encompassing the majority of Minnesota's ombrotrophic (exclusively precipitation-fed) bog peatlands. The average temperature for the mid-century period (2040-2059) was assumed to represent the temperature in 2050. Temperatures between the observed value in 2024 (4.26°C) and the projected value in 2050 (6.33°C) were linearly interpolated.

Finally, many legacy drainage ditches dug during the early 20th century remain on the landscape and lead to carbon losses from the area adjacent to the ditches. In general, these ditch-impacted zones house intact, native plant communities. Using remotely sensed geospatial data, Krause *et al.*[57] determined that annual average carbon losses across Minnesota in ditch-affected areas total 141,000 MT of CO_2-eq per year, though they did not account for fluxes of CH_4 nor N_2O from ditch-impacted areas. We applied this carbon emission value to all years in the dataset.

Combining the carbon flux prediction derived by Hanson *et al.*[58] to 2.353 million acres of intact peatlands with hydrology similar to that of the SPRUCE Experiment, with the average annual losses of carbon from ditch-impacted areas, suggests that Minnesota's intact ombrotrophic bogs and peatlands with legacy drainage have averaged approximately net-zero GHG emissions over recent decades. However, due to projected warming, Minnesota's intact and partially drained peatlands are anticipated to become a consistent annual source of GHGs before 2050, though interactions with hydrologic regimes are harder to predict and will play an important role in the outcome.[59]

Peat harvesting

Peat harvesting has declined in recent decades and is not expected to rebound to historical levels, so emissions from these activities were assumed to remain at levels equal to the 2018-2022 average of 14,329 $MTCO_2$-eq per year.[60]

All other subsectors

Given a lack of any strong expectations for changes in management and extent, GHG fluxes from grasslands, settlements, surface waters, and all non-peatland wetlands were each expected to remain at levels equal to the 2013-2022 average.[61]

Current Policies scenario

Conservation agriculture practices

Minnesota's Climate Pollution Reduction Implementation Grant from the US EPA, entitled *Minnesota climate-smart food systems*, includes conservation agriculture practices to be implemented from 2025 to 2029 that will

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[55] Minnesota Department of Natural Resources Climate Explorer. https://climate-explorer.dnr.state.mn.us/main/historical

[56] Minnesota Climate Mapping and Analysis Tools. MN CliMAT. https://app.climate.umn.edu/

[57] Krause, L., McCullough, K.J., Kane, E.S., Kolka, R.K., Chimner, R.A., and Lilleskov, E.A., 2021. Impacts of historical ditching on peat volume and carbon in northern Minnesota, USA peatlands. *Journal of Environmental Management*, *296*, p.113090.

[58] Hanson, P.J., et al., 2020. Rapid net carbon loss from a whole-ecosystem warmed peatland. (n 48).

[51] Mander, Ü., Öpik, M. and Espenberg, M., 2025. Global peatland greenhouse gas dynamics: state of the art, processes, and perspectives. *New Phytologist*, *246*(1), pp.94-102.

[60] MPCA. 2025. Greenhouse gas emissions in Minnesota 2005-2022 (n 45).

[61] Ibid.

reduce net GHG emissions from agriculture. For simplicity, all of the grant-funded practices are assumed to be implemented in 2027. The expected acreage affected and emission factors associated with each practice are shown in Table 9. Area-weighted averages of emission factors from COMET Planner[62] account for variation in the outcomes of practices in agricultural areas between Minnesota counties (driven by differences in soils and climate), while practice-weighted (i.e., irrigated/non-irrigated, legume/non-legume) averages for cover cropping also account for current rates of how cover crops are typically implemented in Minnesota. Emission factors from MPCA's assessment of GHG emissions reductions from agricultural best management practices[63] were modified to match the scope of the COMET Planner emission factors by excluding changes in emissions associated with on-farm energy use and upstream, out-of-state emissions (most commonly due to forgone synthetic fertilizer production).

Table 9. Conservation agriculture practices expected to be implemented with Minnesota's Climate Pollution Reduction Implementation Grant from the US EPA, entitled *Minnesota climate-smart food systems*.

Practice	Acres	Emissions change factor ($MTCO_2$-eq/acre/year)	Emissions factor source
Add a perennial grass to crop rotations	6,500	-0.2213	COMET Planner area-weighted average
Cover crops	36,000	-0.1105	COMET Planner area- and practice-weighted average
Nutrient management: nitrification inhibitors	100,000	-0.2433	MPCA 2022
Nutrient management: controlled-release fertilizers	100,000	-0.1430	MPCA 2022
Convert croplands to hay lands	20,000	-1.134	COMET Planner area-weighted average
No-till	150,000	-0.4486	COMET Planner area-weighted average
Reduced-till	90,000	-0.2061	COMET Planner area-weighted average
Land retirement: grassland restoration	2,000	-0.4701	COMET Planner area-weighted average

Soil health equipment grants

The Soil Health Financial Assistance Program was established in 2022 by the Governor and the Minnesota Department of Agriculture to provide grants to individuals, groups, and local governments to purchase equipment that promotes soil health practices, such as the implementation of cover crops and conservation tillage. This program was first established as a pilot program and received additional funding in the subsequent legislative sessions.

Anticipated implementation acreage and emission factors are shown in Table 10. We assumed that one-third of the total affected acres in each year would implement either cover crops, reduced tillage, or no-till practices. We acknowledge that some of these practices will occur in combination, but GHG effects are often less than additive, and we preferred a simpler, more conservative approach. All practices were assumed to remain in effect until at least 2050.

In 2024, the Governor and Minnesota Department of Agriculture requested and received funding from the Minnesota Legislature for soil health equipment grants, which allowed for implementation on 35,000 acres.

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[62] Swan, A., Toureene, C., Easter, M., Chambers, A., Brown, K., Williams, S.A., Creque, J., Wick, J., Paustian, K. 2024. COMET-Planner Dataset, Version 3.1, Build 1, and COMET-Planner Report: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning. A companion report to www.comet-planner.com. Downloaded at www.comet-planner.com on August 14, 2024.

[63] MPCA. 2022. Greenhouse gas reduction potential of agricultural best management practices (Revised edition) (n 52)

Assuming the same ratio of affected acres per dollar from 2024, 2025 funding should allow for 140,000 acres of implementation. We assumed that 140,000 acres per year of additional implementation will be funded by the Minnesota Legislature in perpetuity.

Table 10. Anticipated implementation of new practices due to soil health equipment grants.

Practice	Timeframe	Acres	Emissions change factor ($MTCO_2$-eq/acre/year)	Emissions factor source
Cover crops	In 2024	11,667	-0.1105	COMET Planner area- and practice-weighted average
	Annually after 2024	46,667		
No-till	In 2024	11,667	-0.4486	COMET Planner area-weighted average
	Annually after 2024	46,667		
Reduced-till	In 2024	11,667	-0.2061	COMET Planner area-weighted average
	Annually after 2024	46,667		

USDA Regional Conservation Partnership Program

The USDA Regional Conservation Partnership Program (RCPP) is a Farm-Bill-funded program that supports a variety of conservation agriculture practices in Minnesota while working through partnerships with other organizations. Minnesota's Board of Water and Soil Resources was awarded $25 million to support soil health and water quality projects in agricultural areas, many of which provide GHG benefits. The implementation timeline for this program will be 2025-2028, so all acres were conservatively assumed to be implemented in 2027. Anticipated implementation acreage and emission factors are shown in Table 11.

Table 11: Anticipated implementation of new practices due to the USDA Regional Conservation Partnership Program.

Practice	Acres	Emissions change factor ($MTCO_2$-eq/acre/year)	Emissions factor source
Cover crops	208,333	-0.1105	COMET Planner area- and practice-weighted average
No-till	107,143	-0.4486	COMET Planner area-weighted average
Nutrient management	50,000	-0.1448	Weighted average of multiple emission factors from COMET Planner and MPCA 2022
Pasture and hay planting (conversion or improvement of perennials)	1,563	-1.117	COMET Planner area-weighted average
Conservation cover (conversion to perennials)	1,250	-1.117	COMET Planner area-weighted average
Prescribed grazing	4,000	-0.0197	COMET Planner area-weighted average

USDA Advancing Markets for Producers Initiative

This program seeks to expand market opportunities for commodities produced using climate-smart practices. The primary mechanism of importance for GHG forecasting is financial and technical assistance provided to farmers to voluntarily implement new practices on their lands. The implementation timeline is 2024-2026, with most implementation in 2025. For modeling simplicity, all acres are assumed to be implemented in 2025. Anticipated implementation acreage and emission factors are shown in Table 12.

Table 12. Anticipated implementation of new practices due to the USDA Advancing Markets for Producers Initiative.

Practice	Acres	Emissions factor ($MTCO_2$-eq/acre/year, compared to counterfactual)	Emissions factor source
Cover crops	66,425	-0.1105	COMET Planner area- and practice-weighted average
No-till	25,892	-0.4486	COMET Planner area-weighted average
Reduced-till	20,746	-0.2061	COMET Planner area-weighted average
Nutrient management	29,712	-0.1448	Weighted average of multiple emission factors from COMET Planner and MPCA 2022
Conservation crop rotation (adding a high residue crop in the rotation)	3,010	-0.3231	COMET Planner area-weighted average
Pasture and hay planting (conversion or improvement of perennials)	1,580	-1.117	COMET Planner area-weighted average
Prescribed grazing	3,035	-0.0197	COMET Planner area-weighted average

Peatland restoration

Minnesota's Climate Smart Food Systems grant funds the rewetting of 2,500 acres of croplands on fully drained histosols, 2,500 acres of grasslands on fully drained histosols, and 5,000 acres of partially drained peatlands with abandoned but still functioning ditches. These efforts will convert these lands to hydrologically functioning peatlands and are expected to reduce net emissions from these current land uses on drained organic soils. All 10,000 acres are assumed to be rewetted in 2029.

For this analysis, emission factors for fully drained histosols were modified from MPCA's *Greenhouse gas reduction potential of agricultural best management practices*.[64] The scope of this analysis included only in-state emissions, so we ignored changes in out-of-state emissions associated with on-farm energy use and forgone production of synthetic crop chemicals. Importantly, because we used the equation derived by Hanson *et al.*[65] to determine the carbon sink strength of ombrotrophic bog peatlands based on temperature, we also removed the assumed carbon sequestration component of the emission factors derived in MPCA's report (-0.05 $MTCO_2$-eq/acre/year). In the absence of research on the relationship between temperature and carbon fluxes from non-ombrotrophic bogs, this removal of the small annual carbon sequestration term assumes that non-ombrotrophic bogs are net neutral carbon sinks/sources and are unaffected by temperature variations, rather than consistent but small annual carbon sinks. Finally, emission factors were converted to IPCC Fifth Assessment Report 100-year GWPs from Fourth Assessment Report GWPs, as they were reported in MPCA's report. These modifications led to the emission factors shown in Table 13 and Table 14. Given that research on the GHG implications of rewetting partially drained but otherwise intact peatlands is very limited, the emission factor for affected ditch zones of partially drained peatlands after rewetting was taken from an unpublished study led by TerraCarbon based on restoration at Sax-Zim Bog, where the water table was raised from -20 cm to -15 cm (See Couwenberg *et al.*[66] for the quantitative relationship and Blann *et al.*[67] for details on TerraCarbon's analysis). For simplicity, all net emissions reductions were converted to CO_2-eq and applied to

[64] MPCA. 2022. Greenhouse gas reduction potential of agricultural best management practices (Revised edition) (n 52)

[65] Hanson, P.J., et al., 2020. Rapid net carbon loss from a whole-ecosystem warmed peatland. (n 48).

[66] Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A. and Joosten, H., 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. *Hydrobiologia*, *674*(1), pp.67-89.

[67] Blann, K., Lenhart, C., Felice, M., Swope, M., Ettinger, A., Benham, P. 2025. Playbook for Minnesota Peatlands. https://www.nature.org/content/dam/tnc/nature/en/documents/PeatlandPlaybook-Jan25.pdf

relevant soil carbon pools in the existing Minnesota GHG inventory accounting structure. The relevant soil carbon pools to which reductions were applied are grasslands remaining grasslands on organic soils, croplands remaining croplands on organic soils, and intact peatlands.

Table 13. Peatland restoration summary.

Practice	Acres	Combined emissions factor ($MTCO_2$-eq/acre/year, compared to counterfactual)	Emissions factor source
Rewet drained histosols in pasture or grassland	2,500	-8.316	Modified from MPCA 2022
Rewet drained histosol in cropland	2,500	-12.756	Modified from MPCA 2022
Rewet partially drained peatlands within ditch-impacted zones	5,000	-0.575	Couwenberg *et al.* 2011, Blann *et al.* 2025

Table 14. GHG-specific emission factors associated with peatland restoration, expressed in $MTCO_2$-eq/acre/year.

Practice	N_2O-direct	N_2O-indirect volatilization	N_2O-indirect leaching	CH_4	CO_2-soils	CO_2-urea, liming	GHGs-energy
Rewet drained histosols in pasture or grassland	-0.90176	NA	-0.026769	1.45126	-8.7958	0	-0.0434
Rewet drained histosol in cropland	-2.03023	NA	-0.05797	1.53517	-12.1157	-0.02547	-0.0621
Rewet partially drained peatlands within ditch-impacted zones	0	0	0	0.946165	-1.52163	0	0

Biochar production and application

Biochar is a carbon-rich product created through the pyrolysis of biomass, where the biomass is converted to a charcoal-like material by superheating it in an oxygen-limited furnace. The carbon in biochar resists decomposition and has beneficial applications for soil health. This analysis included the impact of commercial-scale biochar facilities. These facilities tend to utilize feedstocks and operate at temperatures such that 80% of the carbon in the biochar is expected to remain after 100 years.[68] Some small-scale, on-site biochar is currently produced through the actions of conservation organizations and soil and water conservation districts in Minnesota; however, details on these activities are not accessible, so we were not able to include their impacts in this analysis.

One such operation is a municipal facility currently under construction in Minneapolis. At this facility, the primary feedstock will be waste wood, pyrolysis will occur at temperatures of 450-600°C, and 500 tons of biochar will be generated annually (James Doten, City of Minneapolis, personal communication). We assumed all biochar will be applied to settlement soils, yielding annual long-term sequestration of 1,129 MT CO_2-eq starting in 2026 and continuing until at least 2050.

Minnesota's Climate Smart Food Systems grant will offset tipping fees for organic materials from Ramsey and Washington counties, which will help fund a facility (Dem-Con HZI Bioenergy) that will generate biochar. We assumed that the average carbon fraction of the feedstocks will be 0.5 and that pyrolysis and gasification will

[68] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf

occur at temperatures greater than 600°C. We also assumed that 100% of the 8,000 tons of biochar generated annually will be applied to croplands on mineral soils, yielding annual long-term sequestration of 10,443 MT CO_2-eq. These emissions reductions are expected to occur in each year from 2027 to 2050. The GHG emissions reductions related to this project due to anaerobic digestion and avoided methane were accounted for within the GCAM model.

Minnesota's Climate Smart Food Systems grant also funds industrial innovations, which may include biochar production. There is potential for one or more additional biochar facilities to be funded by this grant, so we assumed that one facility, similar in scale to Minneapolis' nascent facility, will be funded by this grant. We assumed the primary feedstock would be wood and that pyrolysis would occur at temperatures of 450-600°C. We also assumed that all 500 tons of biochar generated annually will be applied within settlement soils, yielding annual long-term sequestration of 1,129 MT CO_2-eq. These emissions reductions are anticipated to occur in each year from 2027 to 2050.

Potential Policies Pathway scenario

Agriculture-relevant policies

Implement climate-smart soil health practices on 80% of cropland

By 2050, Minnesota could achieve and maintain the adoption of agricultural practices that reduce net GHG emissions on 80% of Minnesota's 21.5 million cropland acres. This strategy includes adopting three practices: no-till or reduced till, use of cover crops where appropriate, and/or implementation of perennial field borders.

Of the 21.5 million acres of total cropland in 2022, 0.76 million acres included cover crops, 1.2 million acres utilized no-till, and 7.9 million acres utilized reduced till, as shown in Table 15.[69] We assumed that all cover crop acres currently occur on the same land as the no-till and reduced till acres, leaving 12.4 million acres that used conventional tillage without cover crops. Minnesota has greater than 99% compliance with its "buffer law," which requires perennially vegetated strips of vegetation of at least 50 feet between fields and natural waterbodies and 16.5 feet between fields and public ditches[70]. The area currently in perennial borders is difficult to estimate, but likely between 0.1 million and 0.5 million acres. We assumed that expanding buffer areas to 1 million acres would remove 1 million acres from the total cropland area. Finally, the only widespread perennial crops currently harvested in Minnesota are hay and haylage, the majority of which is alfalfa. Hay and haylage vary from about 1.2-2.0 million acres harvested per year (USDA NASS). Given the relatively short duration (3-5 years) of alfalfa cultivation on a given field, we treated hay and haylage as conventional row crop acres.

See Table 15 for estimated acreages under various types of management under the Potential Policies Pathway scenario. We assumed that 80% of the acres shifting to no-till practices would also adopt cover crops. We also assumed that total crop acreage would decrease by the amount of newly established field borders but would otherwise remain unchanged. Therefore, of the 12.4 million acres that are currently fully conventional, 1 million acres would be converted to perennial field borders, 1 million acres would be planted with perennial crops, 1.22 million acres would adopt no-till alone, 4.88 million acres would adopt cover crops and no-till, and 4.3 million acres would remain fully conventional. The 0.76 million acres currently in no-till and cover crops would remain unchanged. Of the 7.9 million acres currently in reduced till, 1.58 million acres would become no-till, and 6.32 million acres would become no-till with cover crops. Implementation was assumed to be

[69] USDA National Agricultural Statistics Service, 2022 Census of Agriculture. Complete data available at www.nass.usda.gov/AgCensus

[70] Minnesota Office of the Revisor of Statues. 2025 Statues. https://www.revisor.mn.gov/statutes/cite/103F.48

evenly spread across all types of conversion from 2026 to 2050 (25 years), resulting in the conversion of 0.64 million acres per year.

Table 15. Estimated acres (in millions) under various types of management in 2022 and as modeled under the Potential Policies Pathway scenario in 2050.

Cropland management	Estimated acres (millions), 2022	Percent of total cropland area, 2022	Estimated acres (millions), 2050	Percent of total cropland area, 2050
Conventional	12.4	58%	4.3	21%
Reduced till	7.9	37%	0	0%
No-till	1.2	6%	15.2	74%
Cover crops*	0.76	4%	11.96	58%
Perennial field borders*	NA	NA	1	NA
Perennial crops	NA	NA	1	5%
Total crop acres*	21.5		20.5	

*Total crop acres do not include cover crops nor perennial field borders. Cover crop acres are assumed to occur on the same land as reduced tillage and no-till acres, so their inclusion in the total would result in double-counting. Perennial field borders are not cropped. "NA" means "not applicable."

Emissions reductions were estimated using emission factors derived from the USDA's COMET-Planner Tool, version 3.1.[71] COMET-Planner provides county-level emission factors for a variety of agricultural practices changes. Because these conservation agriculture practices would be adopted across the entire agricultural area of the state, and total cropland areas vary by county, a cropland-area-weighted statewide average emissions factor was used for each practice. Within cover crop scenarios, an area- and practice-weighted emission factor was used, based on current irrigation rates (2.5%, USDA-NASS), no-till (5.6%, USDA-NASS), and whether cover crops are legumes (20%, based on expert opinion). Also, COMET Planner version 3.1 exclusively provides emission factors for cover crop implementation with a 25% or 50% reduction in nitrogen fertilizer with non-legume and legume cover crops, respectively. Therefore, the assumption of nitrogen fertilizer reductions and associated effects on emissions is embedded within all cover crop scenarios. Finally, COMET-Planner doesn't provide an emissions factor for the combined practice of switching from reduced tillage to no-till with cover crops, so the greater of these two single emission factors (switching from reduced till to no-till) was used for all 6.32 million acres that would undergo this transition.

Transition 100% of synthetic nitrogen fertilizers to enhanced-efficiency nitrogen fertilizers

Slow- and controlled-release nitrogen fertilizers, also called enhanced-efficiency nitrogen fertilizers (EENFs), can reduce nitrous oxide emissions from cropland by extending the availability of nitrogenous fertilizers for plant uptake and reducing nitrogen losses to the environment. Examples include polymer- and sulfur-coated urea and nitrification inhibitors.

This strategy aims to transition 100% of synthetic nitrogen fertilizers to slow- and controlled-release versions by 2050. Based on the acreage of major commodity crops in Minnesota, as well as manure availability, we estimate that one-third of acres in Minnesota do not receive synthetic nitrogen fertilizers on an annual basis because nitrogen needs are met through nitrogen-fixing bacteria (legumes), manure amendments, and/or nutrients from preceding cover crops. We assume that of the remaining 14.33 million acres to which synthetic fertilizers are applied, fewer than 10% are currently treated with slow- and controlled-release fertilizers. Beginning in 2026, 4% of the 14.33 million acres currently assumed to be treated with synthetic nitrogen

[71] Swan, A., Toureene, C., Easter, M., Chambers, A., Brown, K., Williams, S.A., Creque, J., Wick, J., Paustian, K. 2024. COMET-Planner Dataset, Version 3.1, Build 1, and COMET-Planner Report: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning. A companion report to www.comet-planner.com. Downloaded at www.comet-planner.com on August 14, 2024.

fertilizers would be treated with EENFs. We assumed that half would be treated with nitrification inhibitors and the other half would be treated with controlled-release nitrogen fertilizers such as polymer-coated urea. Each year thereafter, EENFs would be used on an additional 4% of total acres treated with synthetic nitrogen fertilizers until 2050, at which point they would be applied to 100% of acres. Sales of EENFs would displace sales of common conventional forms such as anhydrous ammonia, conventional urea, and urea ammonium nitrate. Emission factors were taken from MPCA's *Greenhouse gas reduction potential of agricultural best management practices* report.[72]

Implement practices or technologies that reduce livestock-related GHG emissions at most feedlots in Minnesota

Animal agriculture generates significant emissions of methane and nitrous oxide from manure handling and storage, as well as enteric methane emissions (livestock digestion, primarily cattle). Minnesota has large populations of dairy cattle, beef cattle, swine, and poultry, and each animal type has unique manure management practices and, to some extent, GHG-reducing solutions.

Manure management strategy components:

- Use solid-liquid separation, chemical modification, covering and flaring, and/or anaerobic digestion of uncovered storage of untreated manure
- Within swine operations, reduce manure storage time from 12 to 6 months
- Reduce levels of protein in swine and beef diets
- Thermochemical treatment of poultry manure

Emission factors were derived from the USDA's Entity Scale GHG Quantification Guidelines[73] and various other peer-reviewed scientific literature, as shown in Table 16. The potential applicability of a livestock species-specific set of alternative manure management approaches was determined using feedlot permit data. Within each livestock species, we relied on expert opinion to set potential implementation levels across the suite of alternative practices. The reductions expected from each manure management practice were summed across all livestock species. These emissions reductions were scaled up over time at a constant rate and summed with the Current Policies scenario.

Enteric methane emissions can be reduced by using feed additives (e.g., 3-NOP) for beef and dairy cattle fed in confinement, reducing enteric emissions by an estimated 22% and 32% per head, respectively.[74, 75] This strategy would utilize feed additives for 50% of the total confinement-fed population of beef and dairy cattle, estimated to be 25.2% and 80% of beef and dairy cattle, respectively.[76] This is an area of active research and product development with a variety of potential feed additives currently available, under study, and in development; 3-NOP was used as a proxy for this class of methane-reducing feed additives, though applications and results will vary.

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[72] MPCA. 2022. Greenhouse gas reduction potential of agricultural best management practices (Revised edition) (n 52)

[73] Hanson, W.L., C. Itle, K. Edquist (eds). 2024. *Quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity-scale inventory*. Technical Bulletin Number 1939, 2nd edition. Washington, DC: U.S. Department of Agriculture, Office of the Chief Economist.

[74] Feng, X. and Kebreab, E., 2020. Net reductions in greenhouse gas emissions from feed additive use in California dairy cattle. *Plos one*, *15*(9), p.e0234289.

[75] Dijkstra, J., Bannink, A., France, J., Kebreab, E., van Gastelen, S. Antimethanogenic effects of 3-nitrooxypropanol depend on supplementation dose, dietary fiber content, and cattle type. Journal of dairy science. 2018 Oct 1; 101(10):9041–7. https://doi.org/10.3168/jds.2018-14456

[76] Eagle, A.J., A.L. Hughes, N.A. Randazzo, C.L. Schneider, C.H. Melikov, E. Puritz, K. Jaglo, and B. Hurley. 2022. Ambitious Climate Mitigation Pathways for U.S. Agriculture and Forestry: Vision for 2030. Environmental Defense Fund (New York, NY) and ICF (Washington, DC). www.edf.org/sites/default/files/documents/climate-mitigationpathways-us-agriculture-forestry.pdf

Table 16. Utilization of manure management practices and technologies by 2050 under the Potential Policies Pathway scenario.

Livestock species	Typical manure management	Alternative manure management	Technical potential*	Target implementation†	CH_4 emission change factor‡	N_2O emission change factor‡	Reference
Dairy	Liquid/slurry storage	Cover and flare	0.8	0.2	-0.9	0	Hanson, *et al.* 2024[77]
		Anaerobic digestion	0.8	0.1	-0.972	0	Hanson, *et al.* 2024
		Solid liquid separation	0.8	0.3	-0.48	-0.05	Aguirre-Villegas *et al.* 2019[78]
		Slurry acidification	0.8	0.3	-0.64	0	Ambrose, *et al.* 2023[79] [avg. reduction at pH 6]
Swine	Liquid/slurry storage	Solid liquid separation	1	0.1	-0.852	-0.333	Wang *et al.* 2017[80]
		Slurry acidification	1	0.5	-0.71	-0.5	Ma *et al.* 2022[81] [midpoint of effect for both gases]
		Empty deep pits 2x/year (1x in spring) and cold outdoor storage	0.5	0.5	-0.32	0	Hanson, *et al.* 2024
		Lower crude protein diet (from 19% to 15%)	0.5	0.75	0	-0.211	Hanson, *et al.* 2024
		Cover and flare	0.1	0.5	-0.9	0	Hanson, *et al.* 2024
Poultry	Solid with bedding	Thermochemical processing (pyrolysis or gasification)	0.9	0.3	-0.99	-0.99	Hassanein *et al.* 2024a,[82] Hassanein *et al.* 2024b[83]
Beef	Scrape and stack	lower crude protein diet (from 13% to 11.5%)	0.5	0.75	0	-0.24	USDA. 2023[84]

*proportion of emissions addressable by this alternative management practice or technology
†proportion of technical potential addressed within the Potential Policies Pathway scenario
‡proportional change where this alternative is employed relative to the typical manure management

[77] Hanson, W.L., C. Itle, K. Edquist (eds). 2024. *Quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity-scale inventory*. Technical Bulletin Number 1939, 2nd edition. Washington, DC: U.S. Department of Agriculture, Office of the Chief Economist.

[78] Aguirre-Villegas, H.A., Larson, R.A. and Sharara, M.A., 2019. Anaerobic digestion, solid-liquid separation, and drying of dairy manure: Measuring constituents and modeling emission. Science of Tot. Env., 696, p.134059

[79] Ambrose, H.W., Dalby, F.R., Feilberg, A. and Kofoed, M.V., 2023. Additives and methods for the mitigation of methane emission from stored liquid manure. biosystems engineering, 229, pp.209-245.

[80] Wang, Y., Dong, H., Zhu, Z., Gerber, P.J., Xin, H., Smith, P., Opio, C., Steinfeld, H. and Chadwick, D., 2017. Mitigating greenhouse gas and ammonia emissions from swine manure management: a system analysis. Environmental science & technology, 51(8), pp.4503-4511.

[81] Ma, C., Dalby, F.R., Feilberg, A., Jacobsen, B.H. and Petersen, S.O., 2022. Low-dose acidification as a methane mitigation strategy for manure management. ACS Agricultural Science & Technology, 2(3), pp.437-442.

[82] Hassanein, A., Lansing, S. & Delp, D. (2024a). Reducing Greenhouse Gas Emissions through Improved Manure Management (FS-2023-0689). University of Maryland Extension. go.umd.edu/FS-2023-0689.

[83] Hassanein, A., Lansing, S., & Delp, D. (2024b). Using Thermochemical Processes to Handle Agricultural Waste (FS-2023-0688). University of Maryland Extension. go.umd.edu/EBR-2023-0688.

[84] U.S. Department of Agriculture. 2023. Feed and Animal Management for Greenhouse Gas Reduction. Technical Note No. 190-NM-12, August 2023. https://directives.nrcs.usda.gov/sites/default/files2/1719835132/Nutrient%20Management%20190-12%2C%20Feed%20and%20Animal%20Management%20for%20Greenhouse%20Gas%20Reduction.pdf

LULUCF-relevant policies

Achieve a tenfold increase in the annual rate of tree planting in historically forested regions of the state

There are multiple ways to accelerate tree planting in Minnesota cost-effectively, but most of the opportunity lies on privately owned land. The MN DNR's *Forests and Carbon in Minnesota* legislative report contains a discussion of opportunities, strategies, and risks across all forest ownership groups.[85]

We estimated that the current annual rate of tree planting on open lands is 2,800 acres per year.[86] This strategy would increase open land planting tenfold for an additional 25,200 acres each year from 2026 through 2050. We used Forest Inventory Analysis[87] data to determine age-specific annual carbon accumulation rates after afforestation for Northern Lake State forests, assuming that 80% of the new plantings would be softwood species and 20% would be hardwood species. Softwoods sequester approximately 3.3-4.7 metric tons of CO_2-eq per acre per year during the first 50 years after planting, while hardwood forests sequester 0.9-4.2 metric tons of CO_2-eq per acre per year during the first 50 years after planting.

Achieve a fifty percent reduction in annual permanent forest conversion to development and agriculture

Keeping forests as forests is a powerful tool to maintain carbon stocks on the landscape and allow continued carbon sequestration into the future. There are multiple ways to prevent permanent forest conversion. However, the costs of permanent forest protection can be high, especially under pressure from urban and suburban expansion. There is an upper limit of avoided forest conversion based on achieving other social, political, or economic goals (e.g., housing, clean energy, food production).

We estimate that the current rate of conversion of forests to development and agriculture is approximately 29,776 acres per year.[88] Given these considerations, this strategy aims to halve that conversion rate (avoiding the conversion of 14,888 acres per year) starting in 2026 and continuing through 2050.

For stands where conversion would be avoided, we summed the total carbon stock loss avoided and the annual carbon sequestration that would continue until at least 2050. We assumed that the typical stand where conversion would be avoided would be the species-weighted average of Minnesota forests, and that the stand would be 40 years old. We used Forest Inventory Analysis data to determine the average annual carbon stock (131 tons of carbon per acre) and age-specific accumulation rates of relevant forest stands in Minnesota (2.82 to 3.32 tons of carbon per acre per year).

Restore 50% percent of degraded peatlands

The extent of converted cropped, converted pastured, and ditch-impacted zones within partially drained peatlands was recently assessed and reported within TThe Nature Conservancy's 2025 publication *Playbook for MN Peatlands* (326,600, 151,900, and 642,000 acres, respectively). As in the Current Policies scenario, emission reduction factors for fully drained histosols were based on those reported in MPCA 2022,[89] Blann *et al.* 2025,[90] and Couwenberg 2011.[91] "Restoration" in this context refers to the restoration of continuously saturated hydrologic conditions and the diverse native vegetation (which encompasses several categories).

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[85] Minnesota Department of Natural Resources. 2023. Forests and Carbon in Minnesota: Opportunities for Mitigating Climate Change. https://files.dnr.state.mn.us/aboutdnr/reports/legislative/2023/forests-carbon-minnesota-opportunities-for-mitigating-climate-chante.pdf

[86] Henry McCann, Forest Climate Policy Consultant, MN DNR Division of Forestry, personal communication

[87] https://research.fs.usda.gov/programs/fia

[88] Minnesota Department of Natural Resources. 2023. Forests and Carbon in Minnesota. (n 85)

[89] MPCA. 2022. "Greenhouse gas reduction potential of agricultural best management practices (Revised edition)" https://www.pca.state.mn.us/sites/default/files/p-gen4-21.pdf

[90] Kristen Blann, et al., 2025. Playbook for Minnesota Peatlands. (n 67)

[91] Couwenberg, J., et al., 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. (n 66)**Error! Bookmark not defined.**

Under the Potential Policies Pathway scenario, we assumed that 50% of each type of drained peatland would be restored by 2050.

Based on the assumption that half of the area of each type of degraded peatlands could be restored at an equivalent proportional rate from 2029 through 2050, annual emissions from croplands on drained organic soils would be reduced by 2.08 million metric tons (MMT) CO_2-eq, annual emissions from grasslands on drained organic soils would be reduced by 0.63 MMT CO_2-eq, and annual emissions from ditch impacted zones of otherwise intact peatlands would be reduced by 0.184 MMT CO_2-eq by 2050. Restoring these peatlands transitions their land areas into the category of intact peatlands, some of which are assumed to emit carbon at a rate that is dependent on annual average temperature, as described in the section on emissions and sequestration from intact peatlands under the Current Policies scenario. Because temperatures are projected to warm significantly by 2050, increased emissions from intact peatlands partially offset the reductions due to peatland rewetting. The net benefit of such a strategy would increase over time as additional acres are restored each year and would ultimately reduce net emissions by 2.33 MMT CO_2-eq per year by 2050.

Increase the production and land application of biochar tenfold by 2050

Biochar is a product produced by pyrolysis (heating in the absence of oxygen) of organic materials and has a variety of applications, including as a soil amendment. Producing biochar is a mechanism for removing carbon dioxide from the atmospheric carbon cycle by storing it for decades to thousands of years as charcoal. We estimate that by 2027, existing and planned biochar-producing facilities will facilitate the sequestration of approximately 14,183 metric tons of CO_2-eq per year. This strategy would increase production 10-fold, to sequester a total of 141,830 metric tons of CO_2-eq per year by 2050. Emissions reductions are accounted for in the land use type receiving biochar soil amendments, which are assumed to be mineral soil croplands (75%), settlements (10%), forests (10%), and grasslands (5%).

We followed IPCC guidelines to calculate the carbon remaining in soils 100 years after application, based on anticipated pyrolysis temperatures and feedstocks for Minnesota.

Double the production and use of long-lived wood products

Within the context of sustainably managed forests, long-lived wood products can retain carbon for extended periods and be considered an extension of the forest. For the past several decades, paper and paper products have made up the majority of Minnesota's harvested wood product output (Zobel *et al.* 2025). If a large portion of that production could be shifted to longer-lived products such as existing and emerging engineered wood products (e.g., oriented strand board, siding, mass timber), carbon could be stored for much longer periods, resulting in greater accumulation of carbon in harvested wood products pools (e.g., in use and in solid waste disposal sites).

Given that current net additions to the harvested wood products pool total about 1 MMT CO_2-eq per year, and that this rate was 3-4 MMT CO_2-eq per year as recently as the late 1990s and early 2000s, we assume the current rate of net carbon transfer to the harvested wood products pool (after accounting for annual emissions from the decay of existing wood products) could be doubled by 2050. We will utilize actual harvest and production data to estimate decay-related emissions from the current harvested wood products pool, from which we will determine the necessary increase in long-lived wood product production to meet the goal of doubling the annual transfer of carbon to the harvested wood products pool.

Projected emissions from the decay of existing wood products are expected to grow by slightly less than 50% from their current rate, which suggests that contributions to the pool would need to more than double to offset the growing emissions and achieve a doubling of carbon storage in harvested wood products.

Federal policy rollbacks

Within the agriculture and land use, land-use change, and forestry sectors, there are no relevant federal rollbacks that occurred prior to July 2025. While some federal agricultural and conservation programs were funded until at least 2031 in the 2025 reconciliation bill, one program that was not funded and is dependent on the passage of a Farm Bill is the Conservation Reserve Program (CRP). While we cannot know the future of CRP, media reports suggest it could be targeted for removal, and large budget cuts to the Farm Service Administration (which implements CRP and other relevant programs) were proposed in 2025. As such, we estimated the impact of the discontinuation of CRP and the return of these lands to row crop agriculture within the Current Policies scenario after federal rollbacks and the Potential Policies Pathway scenario after federal rollbacks.

As of May 2025, 964,727 acres were enrolled in CRP in Minnesota.[92] The impact of returning grassland CRP to row crop agriculture was estimated to result in a loss of soil carbon equivalent to 6.98 MT CO_2-eq per acre and emissions of nitrous oxide equivalent to 4.028 MT CO_2-eq per acre in the first year after conversion (Ruan and Robertson 2013[93]). In all subsequent years, this change in land use also results in the foregone sequestration of soil carbon equivalent to 0.94 MT CO_2-eq per acre and additional emissions of nitrous oxide equivalent to 0.17 MT CO_2-eq per acre (COMET Planner[94]). We assumed that an equal proportion of the existing CRP acreage would expire and return to row crop agriculture each year from 2025 until 2039.

Federal rollbacks in transportation policy could also impact fluxes from the agriculture and LULUCF sectors in ways that we were not able to assess within the time and resource constraints of this modeling effort. Without federal policies that would drive a rapid transition to electric vehicles, it is assumed that a Clean Transportation Standard (CTS) would be much more reliant on biofuels to meet emissions reduction targets. The anticipated expansion of biofuels derived by the GCAM model does not consider the feasibility of the necessary infrastructure, nor the location or scale of potential land use impacts and associated emissions that could be generated by high biofuel demand. We anticipate the land use change impacts to be somewhat limited because a CTS has strong guardrails against land use conversion, both explicitly and implicitly, via the requirement of ever-decreasing carbon intensity scores. First-generation biofuels (e.g., corn-based ethanol and soy-based biodiesel) would be penalized relatively early in the timeline and phased out in favor of lower carbon-intensity fuels, likely derived from waste and energy-specific crops. A CTS could also be developed to include electrification incentives, which could offset the impact of the shift in federal policies. This is an important topic of further research that will need to be addressed to understand the full lifecycle impacts of transportation fuels and policies in Minnesota.

REMI PI+: Modeling of economic impacts

The economic impacts of Minnesota's Current Policies and Potential Policies Pathway were estimated using the Policies Insight+ model (PI+),[95]developed and maintained by Regional Economic Models, Inc. (REMI), in conjunction with the GCAM modeling described in previous sections. For a list of policies or targets included in each scenario, see Appendix B.

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[92] USDA Farm Service Agency. https://www.fsa.usda.gov/documents/crpmonthlymay2025withpagenumbers

[93] Ruan, L. and Philip Robertson, G., 2013. Initial nitrous oxide, carbon dioxide, and methane costs of converting conservation reserve program grassland to row crops under no-till vs. conventional tillage. *Global Change Biology*, *19*(8), pp.2478-2489.

[94] Swan, A., Toureene, C., Easter, M., Chambers, A., Brown, K., Williams, S.A., Creque, J., Wick, J., Paustian, K. 2024. COMET-Planner Dataset, Version 3.1, Build 1, and COMET-Planner Report: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning. A companion report to www.comet-planner.com. Downloaded at www.comet-planner.com on August 14, 2024.

[95] Regional Economic Models, Inc. (n.d.). *PI+ overview and documentation*. https://www.remi.com/model/pi/

This analysis uses the PI+ version 3.3, specifically calibrated for Minnesota's population, demographics, and employment. The model is a 70-sector, 2-region model. The sectors correspond to 2-digit North American Industry Classification System (NAICS) industries, 3- or 4-digit NAICS industries or industry groupings, and state, local, and federal government. The two regions are the seven-county Twin Cities metro area (Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, Washington) and Greater Minnesota (all other counties).

The PI+ model integrates multiple methodologies—including input–output, computable general equilibrium, econometric, and economic geography modeling—to capture the dynamic interactions between industries, households, and regions. It accounts for how changes in spending, investment, productivity, and population affect output, prices, employment, and income over time. By linking these models, PI+ produces disaggregated estimates of economic activity associated with policy and technology changes. These results should be interpreted as scenario-based approximations rather than precise predictions that reflect stylized representations of economic responses.

Connecting GCAM results to the PI+ model

The PI+ model used outputs from the GCAM results. Energy and technology demand for each sector (residential, commercial, transportation, industry) and the state-supplied electricity generation were computed from the GCAM results, linearly interpolated to create annual estimates, and mapped to the relevant policy variable in PI+. This approach represents a simplified translation of long-run scenario outputs into annual model inputs and is intended solely to ensure internal consistency across scenarios. Results should not be interpreted as forecasts, nor as projections of sector-specific outcomes or official expectations of the State of Minnesota. The following sections describe how GCAM variables were mapped to PI+ policy variables.

Electricity generation

In PI+, electricity generation technologies are represented as Utility industry output (NAICS 22) or custom industry sales/output, which were added in PI+ specifically for this analysis. Utility-scale solar, wind, and biomass generation were modeled as distinct industries to better capture economic and employment effects from clean energy development.[96] Table 17 shows the mapping of GCAM categories to REMI policy variables for electricity generation output. Solar generation includes electricity generated from utility-scale solar installations as well as rooftop solar installations. For the economic modeling, electricity generated from rooftop solar was attributed to residential and commercial buildings and reduced the amount of electricity households and businesses needed to purchase.[97] These representations reflect stylized, scenario-driven assumptions used to approximate how changes in electricity generation in the model scenarios may affect economic activity and should not be interpreted as empirical forecasts or precise projections of future generation levels, technology adoption, or utility behavior. The growth in rooftop solar electricity generation is one key difference between the Current Policies and Potential Policies Pathway electricity generation estimates.

[96] Custom industries used industry input and value-added parameters from REMI's E3 model. Custom industry output was split between Greater MN and the 7-county metro 80/20, which is aligned with the current regional employment mix in QCEW.

[97] Electricity generated from rooftop solar was divided between households and businesses 45% to 55% in line with Minnesota's current residential and commercial solar capacity.

Table 17. Assigning GCAM outputs electricity generation to REMI variables

GCAM electricity generation subsector	REMI policy variable
Biomass	Custom industry output/sales - biomass
Coal	Industry sales (exogenous production) - utilities
Gas	
Hydro	
Nuclear	
Refined liquids	
Rooftop solar photovoltaic	Consumer spending – electricity (as a savings)
Solar	Custom industry output/sales - solar
Wind	Custom industry output/sales - wind

Energy and capital expenditures

Figure 8 summarizes modeled expenditures by sector, distinguishing between energy (fuel) and capital (investment) costs under the Current Policies and Potential Policies Pathway scenarios. In general, capital expenditures, such as building and equipment upgrades, exceed energy consumption expenditures. Total investment between 2025 and 2050 is estimated to be slightly higher in the PPP scenario, which is most likely driven by increased investment from commercial and industrial businesses.[98] Transportation is estimated to exhibit lower investment from businesses and households under the Potential Policies Pathway scenario, likely resulting from efforts to reduce VMT and provide alternative transportation options.

Energy expenditures, such as electricity, natural gas, and refined liquid fuel purchases, are more consistent across the Current Policies and Potential Policies Pathway scenarios. There is little change in the energy expenditure in commercial and residential buildings across the two scenarios due to the expansion of rooftop solar. Over 2025 to 2050, rooftop solar accounts for just under 5% of total residential electricity demand and 6% of total commercial electricity demand in the Potential Policies Pathway, compared to 0.5% and 0.6% of total demand under the Current Policies scenario. Modeled savings from solar generation are estimated to more than offset the slight electricity price increase estimated under the PPP scenario. Over the long term, the PPP scenario transportation fuel expenditures from businesses and households also fall below Current Policies scenario levels, again driven by reducing VMT. The industrial sector is estimated to experience increased energy costs driven by higher prices for fossil fuels under the cap-and-invest policy for large industrial emitters.

[98] Investment from a cap-and-invest policy in the Potential Policy Pathwayscenario are added directly in PI+ and not included GCAM capital expenditure amounts.

Figure 8. Sector capital and energy expenditures under Current Policies and Potential Policies Pathway.

In REMI PI+, GCAM household fuel and capital expenditures for buildings and transportation were assigned to consumer spending categories (commodities). Expenditures from commercial, industrial, and transportation businesses were modeled as exogenous demand for the equipment and fuels purchased. To account for which businesses are making investments or adjusting fuel use, relative capital and fuel costs were adjusted for select industries.[99]

These expenditure patterns reflect scenario-based modeling assumptions and represent internally consistent estimates rather than empirical forecasts. Results are intended to illustrate relative differences between the Current Policies and Potential Policies Pathway scenarios under specified assumptions about technology adoption, prices and behavior. Actual investment decisions, fuel use, and expenditure outcomes will depend on future market conditions, policy implementation details, technological change, and household and firm responses which may differ materially from modeled outcomes. Accordingly, these results should not be interpreted as predictions or commitments associated with regulatory or energy policy decisions.

Table 18 and Table 19 summarize the mapping of GCAM categories to REMI PI+ policy variables for household and business expenditures, which ensured that modeled shifts in technology and fuel use in GCAM translate consistently into changes in sectoral output and investment in PI+.

Table 18. Assigning GCAM household cost outputs to REMI variables

GCAM expenditure	REMI policy variable
End-use capital expenditure (residential buildings)	Consumer spending – household appliances
	Consumer spending – household maintenance
End-use capital expenditure (transportation, LDV)	Consumer spending – new motor vehicles
End-use fuel expenditure (residential buildings)	Consumer spending – electricity
	Consumer spending – natural gas
	Consumer spending – fuel oil and other fuels
End-use fuel expenditure (transportation, LDV)	Consumer spending – motor vehicle fuels, lubricants, and fluids

Table 19. Assigning GCAM business cost outputs to REMI variables

GCAM expenditure	REMI policy variable
End-use capital expenditure (commercial buildings, transportation excl. LDV, industrial)	Exogenous final demand for: machinery manufacturing, motor vehicles, bodies and trailers, and parts manufacturing, other transportation equipment manufacturing
Fuel expenditure – gas	Exogenous final demand for: Utilities
Fuel expenditure – electricity	Exogenous final demand for: Utilities
Fuel expenditure – refined liquids	Exogenous final demand for: Petroleum and coal products manufacturing, chemical manufacturing
Fuel expenditure – H2	Exogenous final demand for: Chemical manufacturing
Fuel expenditure – biomass	Exogenous final demand for: Forestry and logging; fishing, hunting and trapping; wood product manufacturing

[99] Capital and energy expenditures were split among the industries according to industries' emissions shares to reflect that heaviest emitters will require greater investments in clean technologies and clean fuels, see GCAM Capital and Energy Expenditure Assignments to REMI Industries.

Investment in the Potential Policies Pathway scenario

The Potential Policy Pathway scenario includes a cap-and-invest policy that is applied to businesses emitting 25,000 tons of CO_2-eq per year, excluding mining and electricity generation. In a cap-and-invest system, carbon allowances are purchased through auctions, and the revenue raised is then reinvested in businesses and communities to support further emissions reduction efforts. To reflect these investments, $1 billion of cap-and-invest proceeds are distributed across several industries to support additional climate action investment (Table 20).[100, 101, 102]

Table 20. Modeled cap-and-invest investment strategies.

Strategy	REMI Industries	Amount per year
Clean transportation systems and vehicles	Rail transportation, truck transportation, transit and ground passenger transportation; motor vehicles, bodies and trailers, and parts manufacturing	$ 300 million
Clean energy	Utilities and construction	$ 125 million
Energy efficiency and decarbonization	Machinery manufacturing; electrical equipment, appliance, and component manufacturing	$ 200 million
Natural resources and waste	Forestry and logging; fishing, hunting and trapping; waste management and remediation services	$ 250 million
Climate action project facilitation	State and local government	$125 million

Note on aligning GCAM and REMI PI+ baselines

Both GCAM and REMI PI+ include their own baseline ("business-as-usual") trajectories. However, while GCAM explicitly represents the effects of Minnesota's current state and recent federal clean-energy policy shifts, such as the Clean Electricity Standard and the impact of the rollback of IRA tax credits in Minnesota, REMI PI+'s baseline scenario is constructed to reflect macroeconomic and demographic trends under a baseline built from national data and projections.

To ensure the analysis isolates changes driven by GCAM's modeled policies and trends and remains consistent with the emissions and health outcomes analyzed, REMI PI+ variables for demand, output, and consumer spending were adjusted to follow the relative *trajectory* of the corresponding GCAM variables rather than the absolute levels. In other words, the REMI PI+ baseline levels were retained, but their year-to-year growth or decline rates were scaled to align with GCAM results.

The only exceptions are capital costs and fuel prices, which REMI PI+ represents as Minnesota's relative costs compared with national averages. Because GCAM's cost outputs reflect modeled expenditures by Minnesota consumers and businesses rather than changes in national price levels, fuel and capital costs were entered in REMI PI+ as net changes between GCAM and REMI PI+ values. This approach implicitly assumes that state-level policies affect costs within Minnesota without materially altering national price trajectories.

[100] Irani, D., Francis, S., Menking, C., Prasai, R., Taylor, A., & Wetzler, N. (2023). Economic and fiscal impacts of Maryland's greenhouse gas reduction policies. Towson University, Regional Economic Studies Institute. Available at: https://mde.maryland.gov/programs/air/ClimateChange/Maryland%20Climate%20Reduction%20Plan/Economic%20Impact%20Analysis.pdf

[101] California Air Resources Board. (2017). Appendix E: Economic analysis [Appendix to the 2017 Scoping Plan]. https://ww2.arb.ca.gov/sites/default/files/classic/cc/scopingplan/app_e_economic_analysis_final.pdf

[102] Washington State Department of Ecology. Auction revenue investment under the Climate Commitment Act. https://ecology.wa.gov/air-climate/climate-commitment-act/auction-revenue

Methods: Health and economic modeling

In addition to GHG forecasting, the Climate Change Subcabinet conducted health and economic forecasting using the GHG forecasting scenarios to understand impacts. The methods for this work are included below.

COBRA: Modeling health impacts

Health impacts were modeled using the EPA's Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) version 5.1.[103] A screening model widely used in the research community, COBRA is a free, easy-to-use EPA model for preliminary analysis of health impacts and monetized benefits from environmental policy changes. COBRA models the incidence rates and corresponding economic impacts of more than a dozen health outcomes associated with five co-pollutants: fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_X), ammonia (NH_3), and volatile organic compounds (VOCs). These pollutants lead to higher concentrations of $PM_{2.5}$ and ozone in Minnesota's air, which have been shown to cause many respiratory and cardiovascular health outcomes, including early deaths.

The health impacts of the Potential Policies Pathway and Net-Zero Pathway scenarios relative to the Current Policies scenario were modeled in COBRA in five-year increments between 2030 and 2050. The modeling results for each year provide a snapshot of the co-pollutant emissions reductions and the resulting health benefits delivered in each year from the additional policies and actions in the Potential Policies Pathway after federal rollbacks and Net-Zero Pathway scenarios relative to the Current Policies after federal rollbacks scenario. Additionally, to assess the health impacts of the federal rollbacks, COBRA was also used to estimate the health benefits in the Potential Policies Pathway scenario before federal rollbacks, compared to the Potential Policies Pathway scenario after federal rollbacks. Finally, to assess how the cap-and-invest policy contributes to health impacts from co-pollutant emissions, COBRA was used to estimate the health benefits in the Potential Policies Pathway scenario compared to the Potential Policies Pathway without a cap-and-invest policy.

COBRA uses a series of source-receptor matrices to calculate the county-level impacts of air quality changes based on known emissions sources in those locations. To match the sources between the GCAM-USA and COBRA models, the GLIMPSE-to-COBRA bridge spreadsheet developed by Dr. Dan Loughlin at the EPA was used.[104] This tool allowed the co-pollutant emissions outputs from GCAM-USA to serve as inputs for COBRA, which translated those emissions into PM2.5 and ozone ambient air quality concentrations and resulting health outcomes in each of Minnesota's 87 counties in five-year increments from 2030-2050.

COBRA has built-in population, baseline health incidence files, air quality concentration-response functions for $PM_{2.5}$ and ozone for a variety of health outcomes, and health impact valuation functions for those health outcomes. No changes were made to these default settings. The only custom COBRA inputs were the baseline and policy-scenario emissions files derived from GCAM-USA results. The GCAM-USA co-pollutant emissions under the Current Policies scenario served as the COBRA baseline emissions. To estimate the additional health benefits of the Potential Policies Pathway scenario, the GCAM-USA co-pollutant emissions for that scenario were used as the policy scenario in COBRA. Similarly, to estimate the additional health benefits that would be achieved in the Net-Zero Pathway scenario, the GCAM-USA co-pollutant emissions for that scenario were used as the policy scenario in a separate COBRA model run.

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[103] Available at: https://www.epa.gov/cobra

[104] GLIMPSE-to-COBRA bridge. Available at: https://catalog.data.gov/dataset/glimpse-to-cobra-bridge-spreadsheet-v2024-08-23

Finally, COBRA requires the user to choose a discount rate to apply to the monetized value of the projected health benefits. This discount rate aids in determining the current value of a future benefit, with higher discount rates spurring a lower value on future benefits.[105] COBRA provides a default discount rate of 2.0%, which was used for this analysis. Best practices in the scientific literature generally recommend a 2% discount rate for the valuation of climate mitigation benefits.[106]

By default, COBRA generates results in 2023 dollars for monetized values. Depending on the analysis year chosen, different income levels are employed (2016, 2023, 2028). The 2028 income level was used in this analysis to be consistent with the default settings described above. COBRA assumes that the willingness to pay for risk reductions in mortality and other health impacts will increase as real income increases, in line with the best available research.[107]

Given that a majority of economic benefits come from avoided mortality, it is important that avoided mortality is properly defined and understood. The EPA estimates the monetary value of avoided mortality based on the value of a statistical life (VSL).[108] Many studies were aggregated to determine the appropriate VSL, and it is a sum of numerous small risk reductions for many people.[109] Additionally, the estimates of avoided mortality occur over a 20-year period, and COBRA employs a lag structure in which 30% of premature deaths happen in the first year, 50% happen in years 2-5, and 20% in years 6-20. Thus, for example, as reported in the results section below, when the avoided mortality benefit resulting from lower co-pollutant emissions in the Potential Policies Pathway scenario than in the Current Policies scenario in the year 2050, avoided deaths over the 2050-2070 period are considered. The COBRA documentation notes that the value of a statistical life and its corresponding monetary value is not the same as the value of an individual life. See the COBRA User's Manual for further information.[110]

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[105] Priest, B.B. Discounting 101, 2022. https://www.rff.org/publications/explainers/discounting-101/ (accessed 2025-11-24).

[106] Nesje, F.; Drupp, M. A.; Freeman, M. C.; Groom, B. Philosophers and Economists Agree on Climate Policy Paths but for Different Reasons. Nat. Clim. Change 2023, 13 (6), 515–522. https://doi.org/10.1038/s41558-023-01681-w.

[107] *User's Manual for the Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) Version 5.2*; United States Environmental Protection Agency: Washington, DC, 2025. https://www.epa.gov/system/files/documents/2025-03/cobra-user-manual-v5.2.pdf.
pdf (accessed 2025-11-24).

[108] Ibid.

[109] Ibid.

[110] Ibid.

Results: Greenhouse gas forecasting

Results from the GCAM-USA-CGS model and the agriculture and LULUCF forecasts were combined for statewide comparisons of GHG emissions impacts. The scenarios reflect the results after federal rollbacks, unless explicitly comparing the impacts of the rollbacks.

Comparison of Potential Policies Pathway and Current Policies scenarios

Statewide net GHG emissions

Minnesota's current statutory goals are to reduce total statewide greenhouse gas emissions by 50% from a 2005 baseline by 2030 and achieve net-zero emissions by 2050, as well as to reduce transportation emissions by 50% by 2030, 65% by 2035, and 80% by 2040. Minnesota has made substantial progress toward reducing GHG emissions, mainly from electric power generation, but remains above the statutory goal levels as of 2025 (Figure 9).

Full implementation of Minnesota's current policies would reduce GHG emissions by 28% in 2030 and 40% by 2050 relative to a 2005 baseline (Table 21). These actions fall short of the reductions necessary to meet our goals.

Figure 9. Historical total statewide GHG emissions (2005-2020) and projected (2020-2050) emissions under the Current Policies and Potential Policies Pathway scenarios, compared to statutory GHG emission reduction goals.
Projected emissions (2020-2050) were estimated in 5-year increments and calibrated to the historical emissions (2005-2022) at 2020 levels.

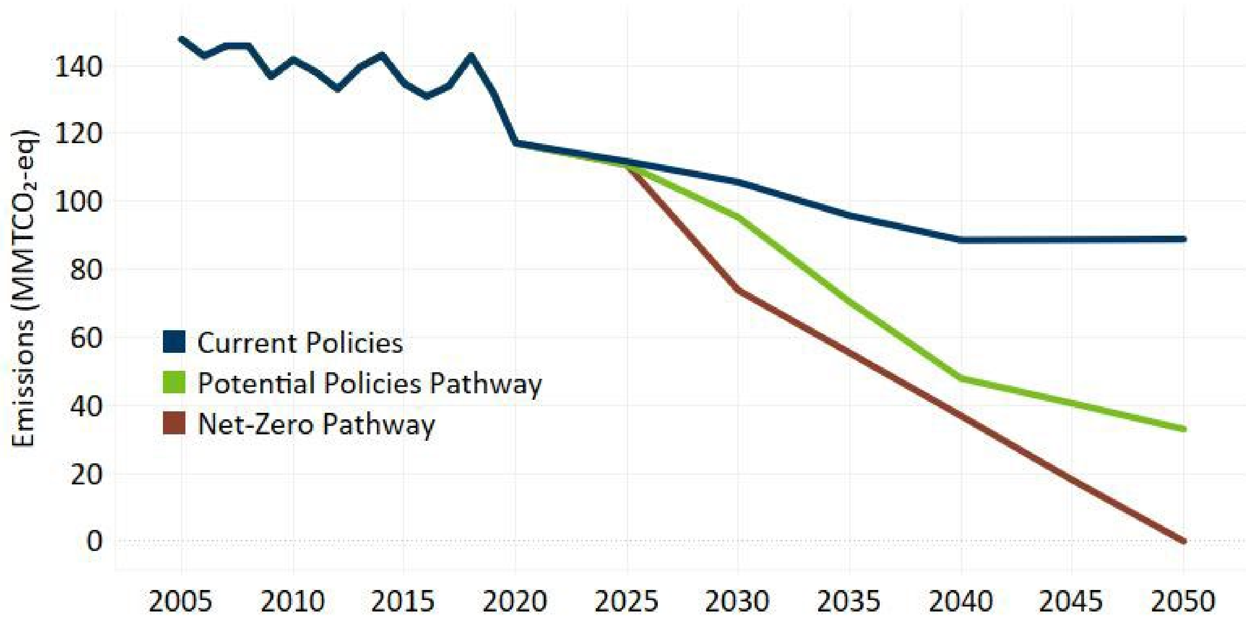


Table 21. Forecasted net emissions from Current Policies by sector and net total.
Results are reported in million metric CO_2-equivalent tons ($MMTCO_2$-eq) for the estimated annual emissions and the calculated change from the 2005 historical baseline. A negative value for emissions indicates carbon sequestration and storage. A positive change indicates an increase over the baseline, and a negative change indicates a reduction from the baseline. A calculated percent change from the baseline is also included.

Sector	2005 emissions ($MMTCO_2$-eq)	2030 emissions ($MMTCO_2$-eq)	2050 emissions ($MMTCO_2$-eq)	Change from 2005 to 2030 ($MMTCO_2$-eq)	Change from 2005 to 2050 ($MMTCO_2$-eq)	Change from 2005 to 2030 (%)	Change from 2005 to 2050 (%)
Electricity	52.0	17.5	0.3	-34.5	-51.7	-66.3%	-99.4%
Transportation	39.1	27.5	24.4	-11.6	-14.7	-29.7%	-37.6%
Buildings	14.0	17.4	15.3	+3.4	+1.3	+24.3%	+9.3%
Industry	19.3	21.5	20.6	+2.2	+1.3	+11.4%	+6.7%
Waste	2.5	1.6	1.8	-0.9	-0.7	-36.0%	-28.0%
Agriculture	30.5	30.9	30.7	+0.4	+0.2	+1.3%	+0.7%
LULUCF	-9.6	-10.9	-4.2	-1.3	+5.4	+13.5%	+56.3%
Net GHG total	147.7	105.7	88.9	-42.0	-58.8	-28.4%	-39.8%

The Potential Policies Pathway achieved a greater reduction in GHG emissions than the Current Policies scenario, reducing GHG emissions by 34% by 2030 and 77% by 2050, especially within the transportation, industrial, and agricultural sectors (Table 22, Table 23, and Figure 10). Discussion of sector-specific policy impacts and results follows in corresponding sections.

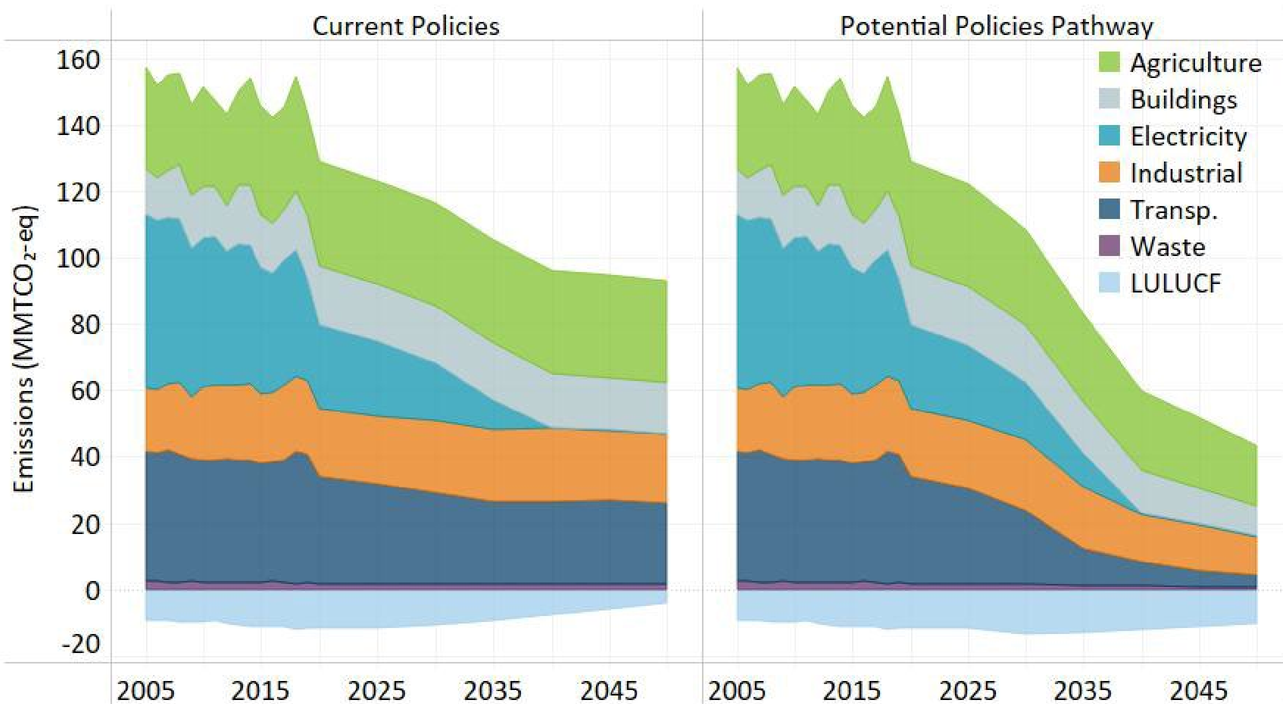
Table 22. Forecasted emissions from Potential Policies Pathway by sector and net total.
Results are reported in CO_2-equivalent million metric tons ($MMTCO_2$-eq) for the estimated annual emissions and the calculated change from the 2005 historical baseline. A negative value for emissions indicates carbon sequestration and storage. A positive change indicates an increase over the baseline, and a negative change indicates a reduction from the baseline. The calculated percent change from the baseline is also included.

Sector	2005 emissions ($MMTCO_2$-eq)	2030 emissions ($MMTCO_2$-eq)	2050 emissions ($MMTCO_2$-eq)	Change from 2005 to 2030 ($MMTCO_2$-eq)	Change from 2005 to 2050 ($MMTCO_2$-eq)	Change from 2005 to 2030 (%)	Change from 2005 to 2050 (%)
Electricity	52.0	17.0	0.4	-35.0	-51.6	-67.3%	-99.2%
Transportation	39.1	22.5	3.4	-16.6	-35.7	-44.5%	-91.3%
Buildings	14.0	17.2	8.9	+3.2	-5.1	+22.9%	-36.4%
Industry	19.3	21.4	11.8	+2.1	-7.5	+10.9%	-38.9%
Waste	2.5	1.4	0.8	-1.1	-1.7	-44.0%	-68.0%
Agriculture	30.5	29.2	18.2	-1.3	-12.3	-4.3%	-40.3%
LULUCF	-9.6	-13.4	-10.4	-3.8	-0.8	-39.6%	-8.3%
Net GHG total	147.7	95.3	33.0	-52.4	-114.7	-35.5%	-77.7%
Additional emissions reductions needed to meet targets		21.5	33.0				

Table 23. Change in emissions from the Potential Policies Pathway compared to the Current Policies, by sector and net total.

Sector	2030 Emissions Change ($MMTCO_2$-eq)	2050 Emissions Change ($MMTCO_2$-eq)
Electricity	-0.5	+0.01
Transportation	-5.0	-21.0
Buildings	-0.2	-6.4
Industry	-0.1	-8.8
Waste	-0.2	-1.0
Agriculture	-1.7	-12.5
LULUCF	-2.5	-6.2
Net GHG change	**-10.4**	**-55.9**

Figure 10. Comparison of sector emissions under the Current Policies and Potential Policies Pathway scenarios. Projected emissions (2020-2050) were estimated in 5-year increments and calibrated to the historical emissions (2005-2022) at 2020 levels.



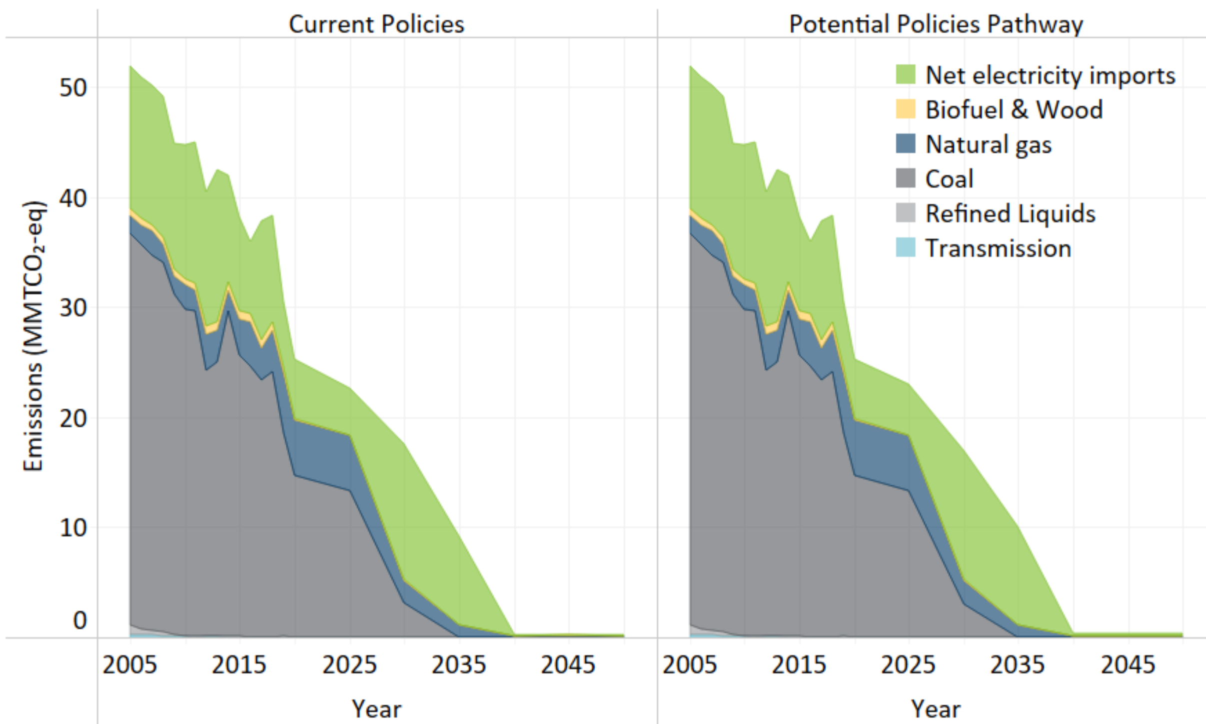
Electricity

Historically, changes in the mix of fuels used to generate electricity have been associated with emission reductions from electric utilities by over 50%, and planned electricity generation changes were implemented in the model, which continue to reduce emissions further (Figure 11). This progress was forecast to continue under the law requiring Minnesota's electricity to reach net-zero emissions by 2040. To achieve this requirement, existing generation facilities may continue operating and purchase Renewable Energy Credits as offsets, new renewable generation capacity may be built in Minnesota, and electricity may be supplied from grid resources in accordance with Clean Electricity Standard (CES) requirements.

The electricity sector exhibited very similar forecasted GHG emissions under the Potential Policies Pathway and Current Policies scenarios because the emission reductions were primarily driven in the model by the CES, which was included as a current policy, and no further sector-specific policies were assumed.

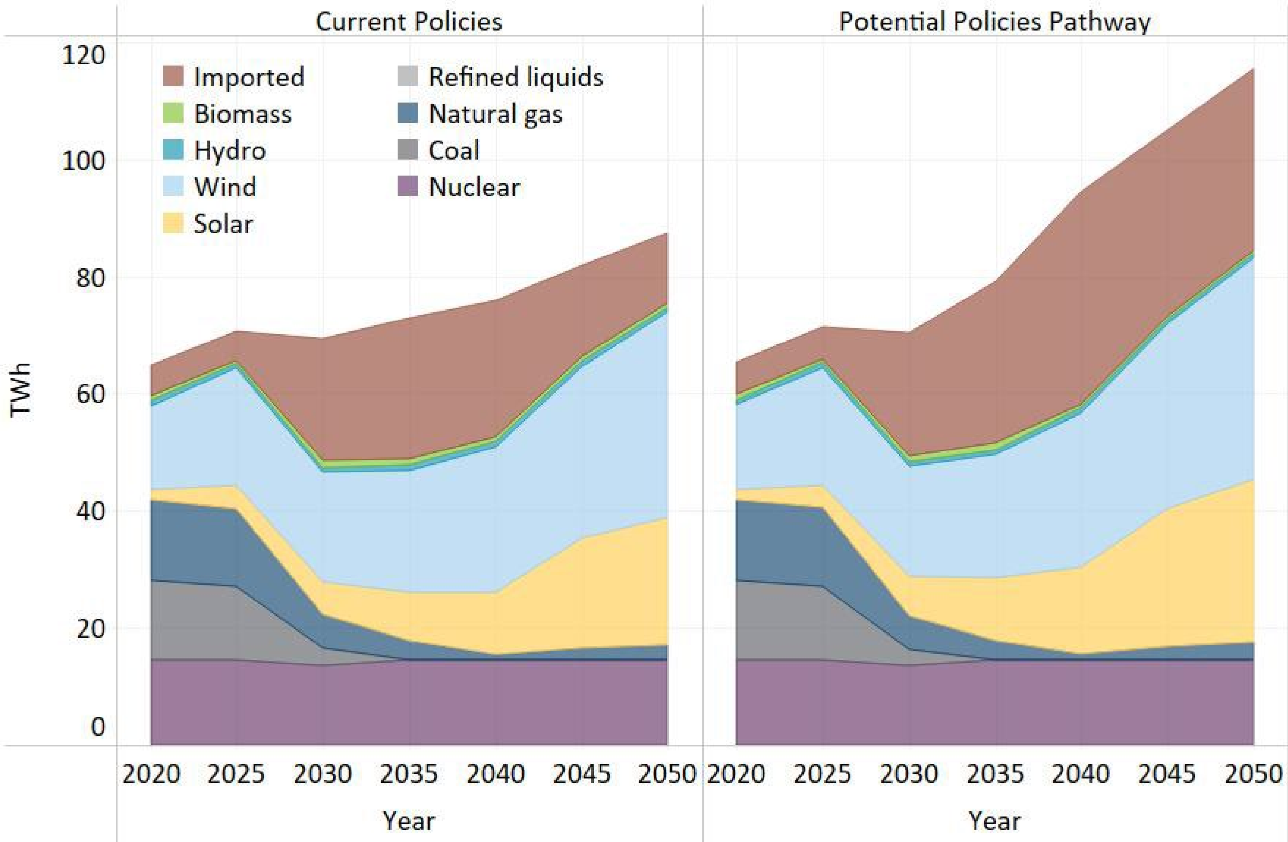
Figure 11. Comparison of electricity sector emissions under the Current Policies and Potential Policies Pathway scenarios.

Projected emissions (2020-2050) were estimated in 5-year increments and calibrated to the historical emissions (2005-2022) at 2020 levels.



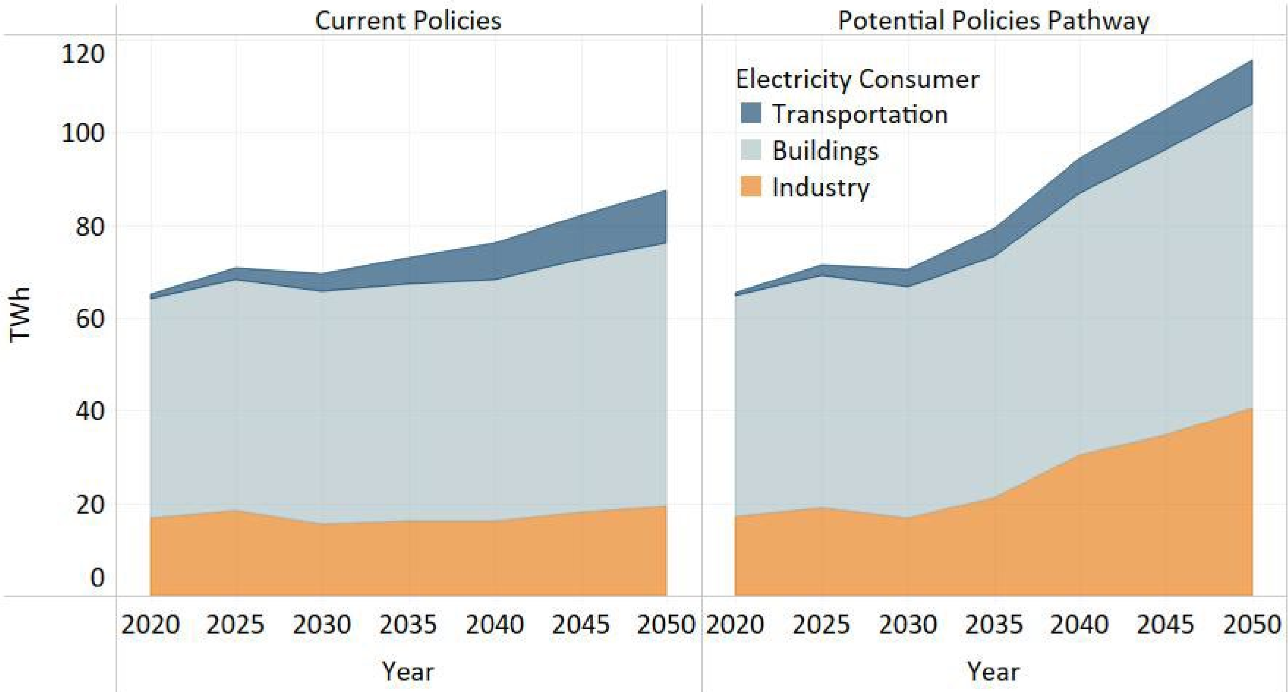
While emissions were similar in the modeled results across the Current Policies and Potential Policies Pathway scenarios because of the constraint of the Clean Electricity Standard, electricity demand differed across scenarios due to policies that incentivized electrification. Under the Potential Policies Pathway scenario, electricity supply was estimated to increase to meet higher modeled demand associated with electrification. This increased supply of electricity was represented as being met primarily by out-of-state generation that meets Minnesota Clean Electricity Standards, with some additional modeled growth in in-state solar and wind generation (Figure 12).

Figure 12. Projected electricity generation (TWh) by energy inputs under the Current Policies and Potential Policies Pathway scenarios.



The greatest difference in electricity consumption under the Potential Policies Pathway was forecasted to occur in the industrial sector (Figure 13). Under Current Policies, industrial electricity demand was forecast to decrease in the near term and increase by approximately 2.5 Terawatt-hours (TWh) by 2050, compared to 2020. By contrast, under the Potential Policies Pathway, industrial electricity demand was forecast to decrease in the very near term due to federal policy rollbacks, then increase quickly and, by 2050, exceed 2020 demand by 23 TWh. Electricity use for building operations was also forecast to increase significantly under the Potential Policies Pathway. In addition, lower electricity demand was projected in the forecast for the transportation sector, resulting from the overall forecasted reduction in energy demand from the transportation sector and reflecting the assumption that federal waivers allowing Minnesota to adopt electric vehicle sales standards were revoked.

Figure 13. Projected electricity consumption (TWh) by consumer under the Current Policies and Potential Policies Pathway scenarios.



Buildings and energy use

Energy use in residential and commercial buildings, as modeled in GCAM, encompasses the majority of emissions historically tracked in the residential and commercial sectors of the GHG Inventory. These emissions have historically fluctuated with the weather and heating degree days and exhibit variability in the historical data. In the forecasted scenarios, variability in emissions from natural gas use was smoothed by using average weather conditions, but it is likely to continue to show annual variation. Natural gas and propane are primarily used in buildings for space heating, as well as for cooking, water heaters, clothes dryers, and other appliances. Carbon storage in buildings occurs in the inventory when wood used in construction exceeds wood stores removed through housing demolition; this source was not explicitly forecasted in future scenarios, though it appears in the historical inventory.

Both greenhouse gas emissions and energy use were forecast to decline more under the Potential Policies Pathway scenario than under the Current Policies scenario (Figure 14). Most of the forecasted emissions reductions were attributed to the electrification of natural gas and propane heating (Figure 16, Figure 17). Buildings sector emissions in 2050 were forecasted in the model to be approximately 6.4 $MMTCO_2$-eq lower under the Potential Policies Pathway than Current Policies, or a forecasted reduction of approximately 42% (Figure 15).

Figure 14. Comparison of buildings sector emissions (MMTCO$_2$-eq) from residential and commercial buildings under Current Policies and Potential Policies Pathway scenarios.

Projected emissions (2020-2050) were estimated within the model in 5-year increments and aligned with historical emissions (2005-2022) at 2020 levels.

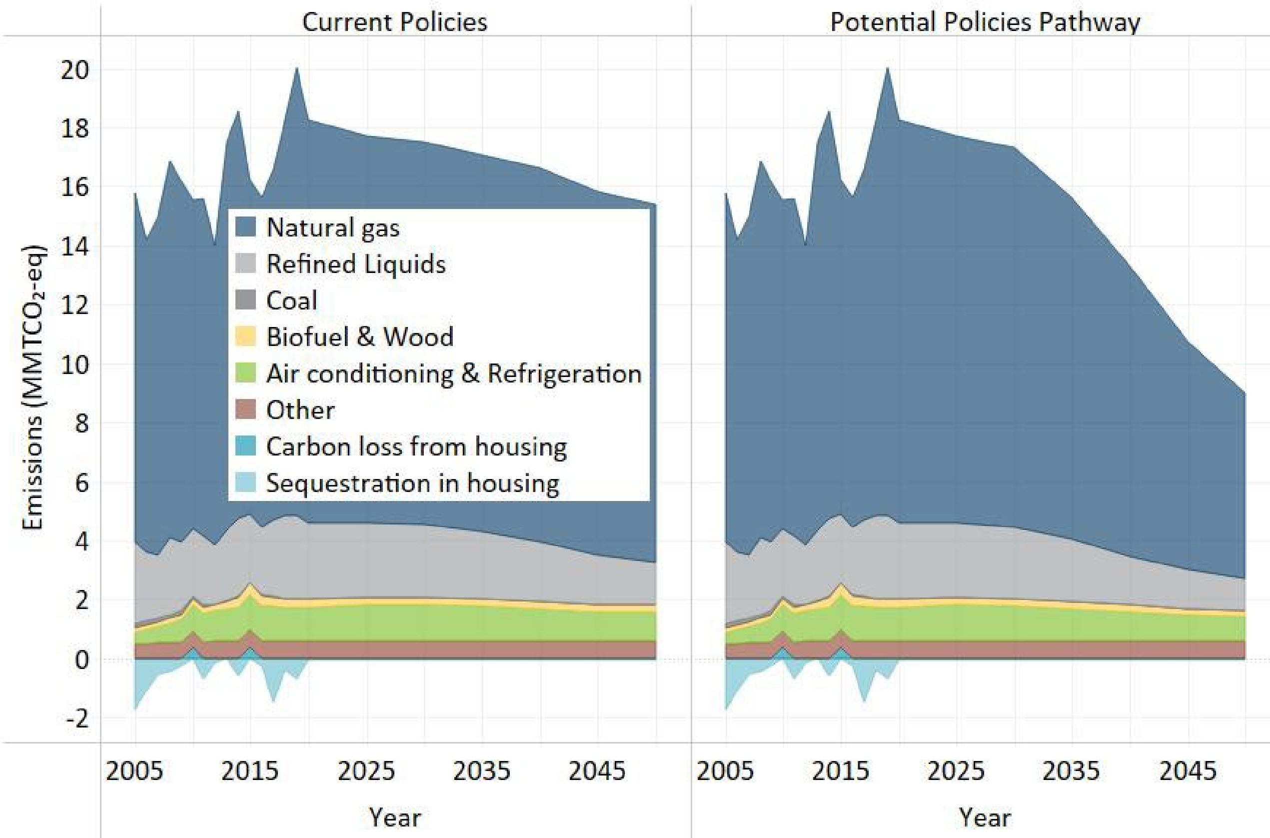
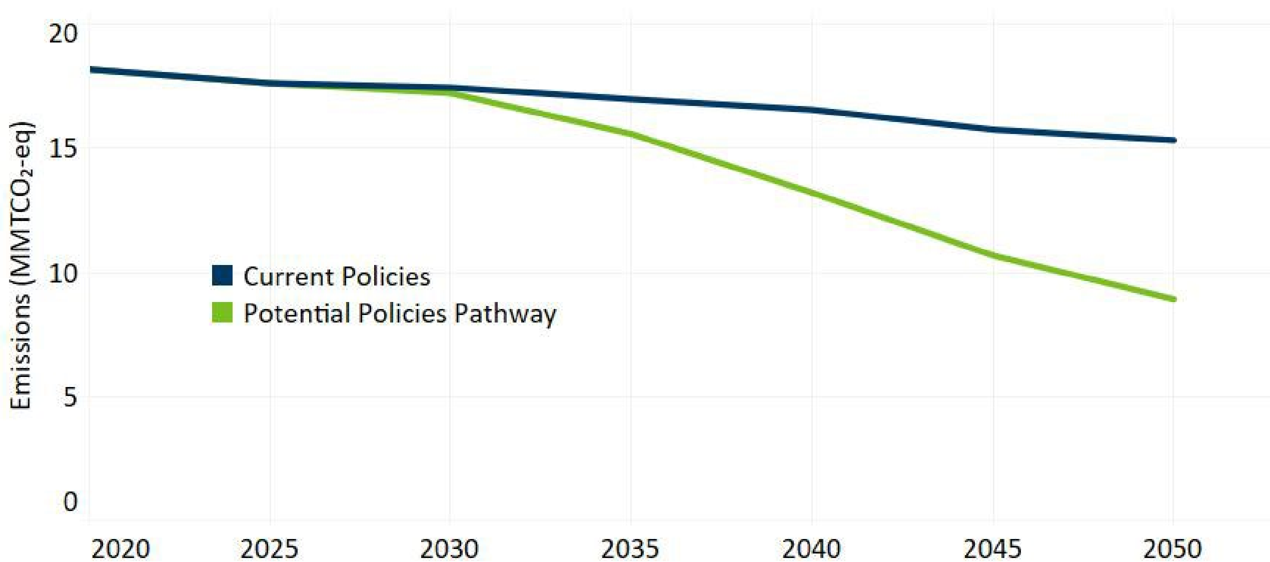


Figure 15. Comparison of projected total residential and commercial buildings sector emissions (MMTCO$_2$-eq) under Current Policies and Potential Policies Pathway scenarios.



Residential and commercial building energy use was analyzed within the model, disaggregated by end use, including space heating, hot water, lighting, cooking, cooling, ventilation, and refrigeration. The largest forecasted reductions in energy use under the Potential Policies Pathway occurred in heating end uses for residential and commercial buildings (Figure 16), driven by modeled weatherization and efficiency improvements. Modeled energy supply by source also indicates that electrification reduces direct fossil fuel use in residential and commercial buildings. (Figure 17).

Figure 16. Projected energy use (EJ) in commercial and residential buildings by major category under the Current Policies and Potential Policies Pathway scenarios.

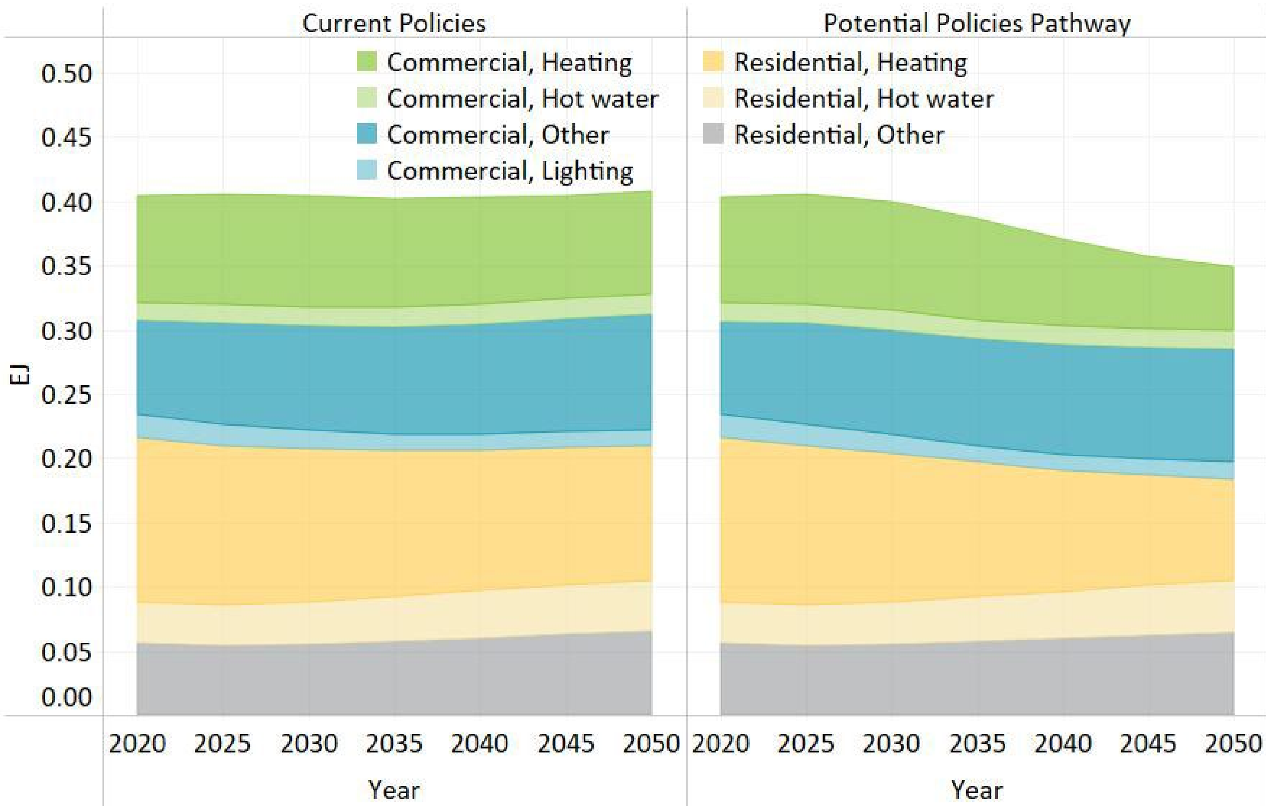
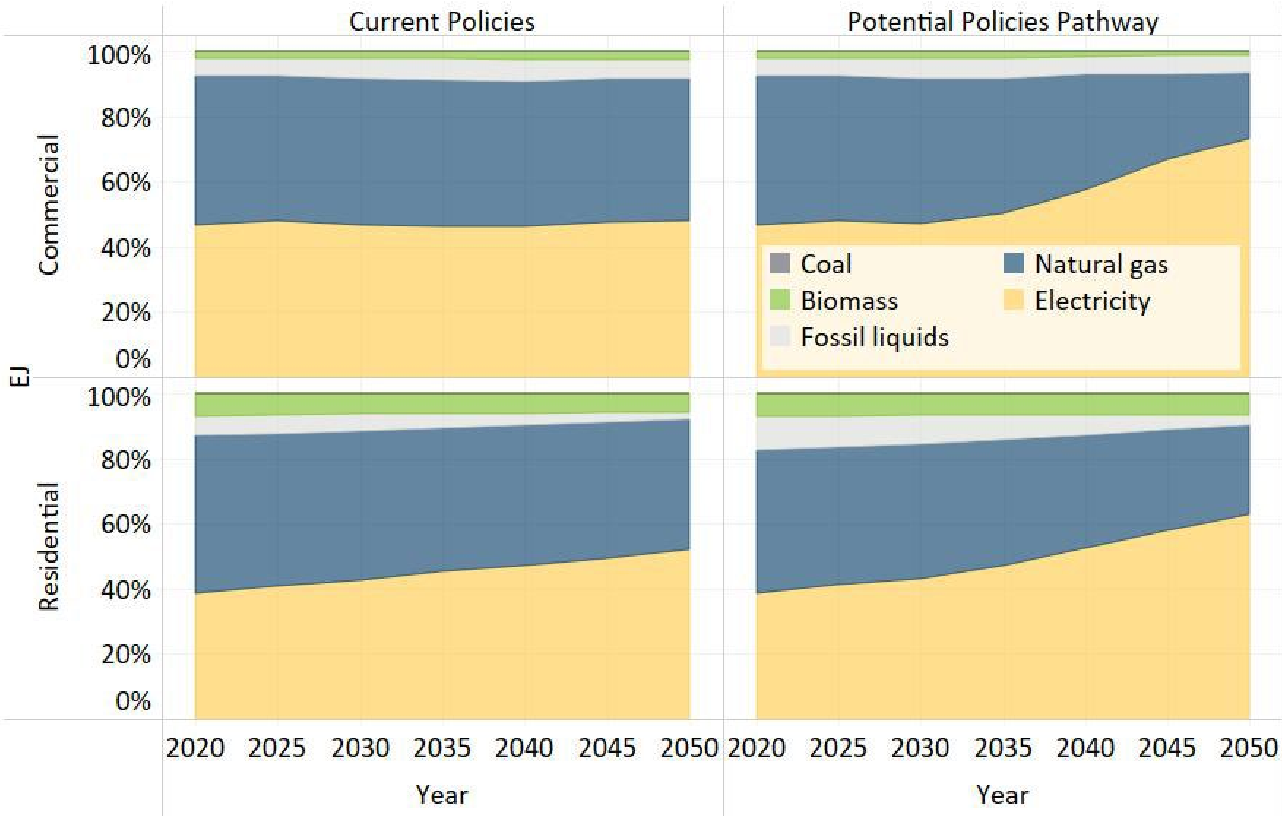


Figure 17. Proportion of energy use (EJ) in residential and commercial buildings projected under the Current Policies and Potential Policies Pathway scenarios by energy input.



Transportation

Current federal and state policies were forecasted to reduce greenhouse gas emissions from transportation. However, the Potential Policies Pathway scenario showed a significant impact from additional potential policies to reduce emissions. The Clean Transportation Standard was the primary driver of reductions in the Potential Policies Pathway and was especially impactful at reducing emissions from passenger cars, light-duty, and heavy-duty trucks (Figure 18). Transportation sector emissions in 2050 were approximately 21.0 $MMTCO_2$-eq lower under the Potential Policies Pathway than Current Policies, or about 86% lower (Figure 19). The passenger transportation services were constrained by the modeling assumption that actions to improve transportation options would reduce vehicle miles traveled. Emission reductions beyond those achieved by less driving were not achieved by further limiting services or choice; rather, they were achieved through low-carbon-intensity fuels and compatible vehicles.

Figure 18. Comparison of transportation sector emissions under Current Policies and Potential Policies Pathway scenarios.

Projected emissions (2020-2050) were estimated in 5-year increments and calibrated to the historical emissions (2005-2022) at 2020 levels.

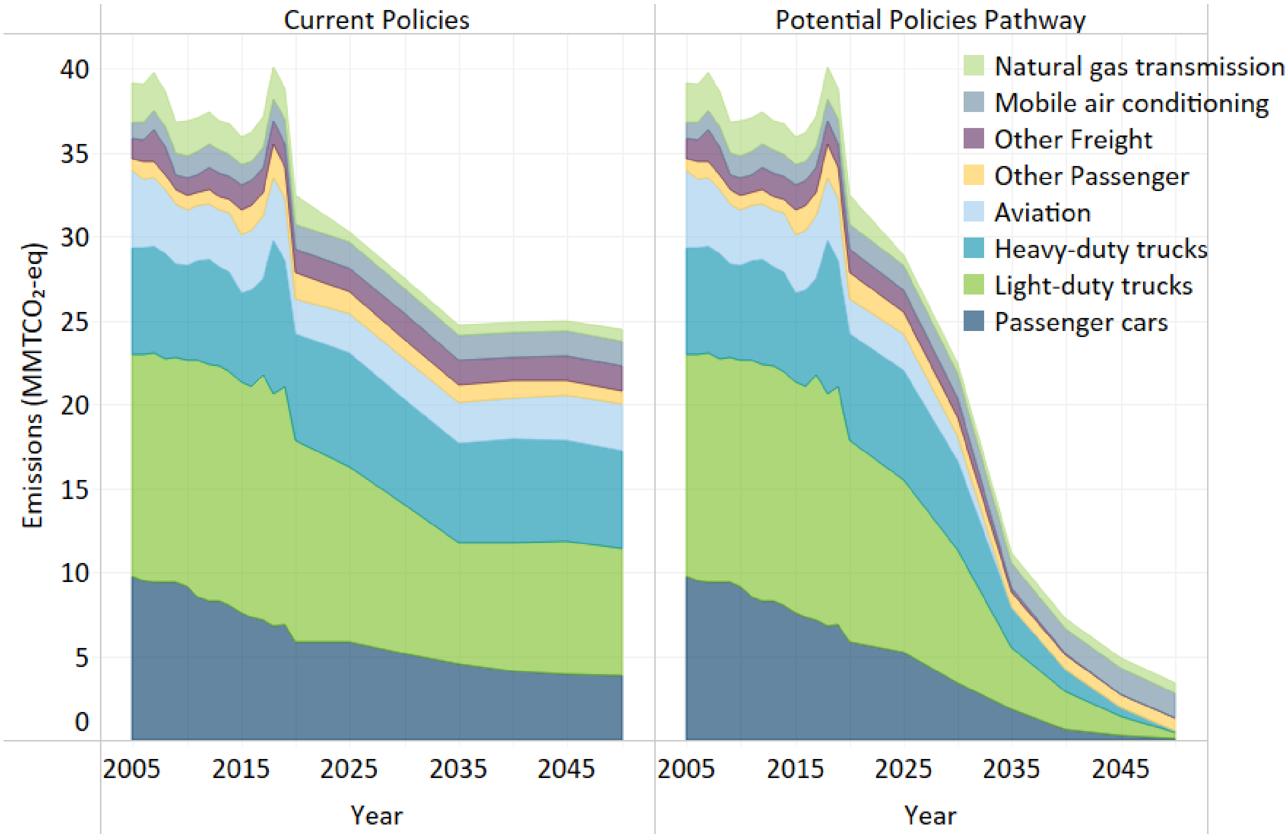
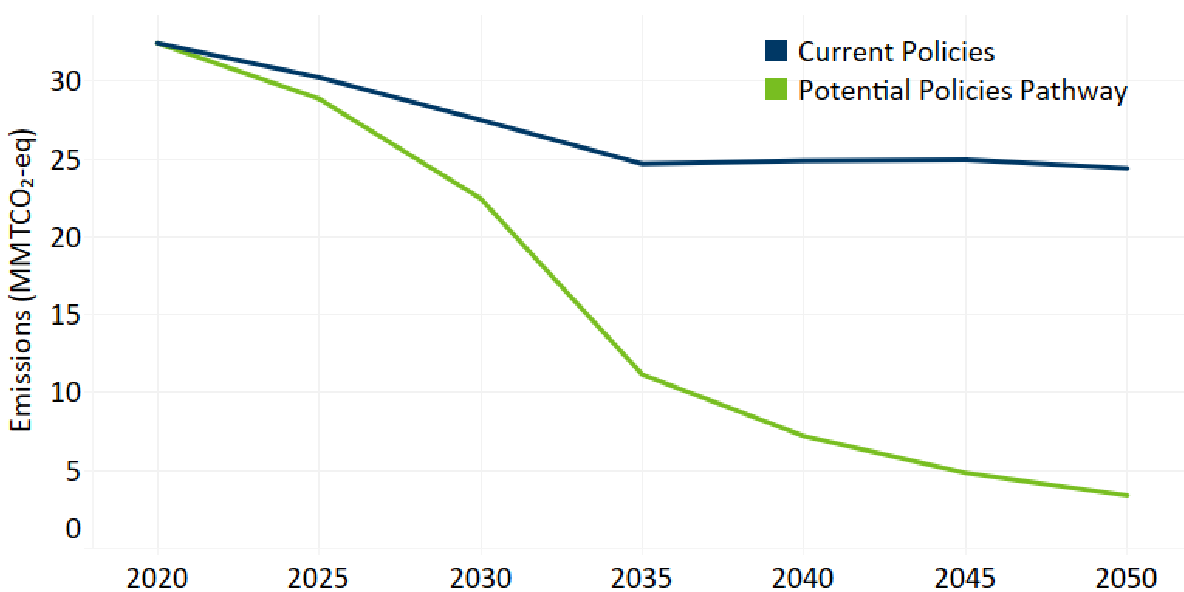


Figure 19. Comparison of projected total transportation sector emissions (MMTCO$_2$-eq) under Current Policies and Potential Policies Pathway scenarios.



Industrial fuel use and processes

The industrial sector has seen increased emissions since 2005, highlighting the lack of policy development and the challenge of reducing emissions from the industrial sector.

Under the Potential Policies Pathway scenario, efficiency standards and a cap-and-invest policy have a strong impact on reducing emissions after 2030. Federal policy rollbacks halted near-term incentives to transition from fossil fuels, but state policy implementation was forecast to reduce emissions from natural gas and petroleum-based fuels and to reduce some coal-use emissions (Figure 20). Emissions in 2050 were forecasted to be approximately 8.9 MMTCO$_2$-eq lower under the Potential Policies Pathway scenario than the Current Policies scenario, or about 43% lower (Figure 21).

Figure 20. Industrial sector emissions (MMTCO$_2$-eq) under the Current Policies and Potential Policies Pathway scenarios. Projected emissions (2020-2050) were estimated in 5-year increments and calibrated to the historical emissions (2005-2022) at 2020 levels.

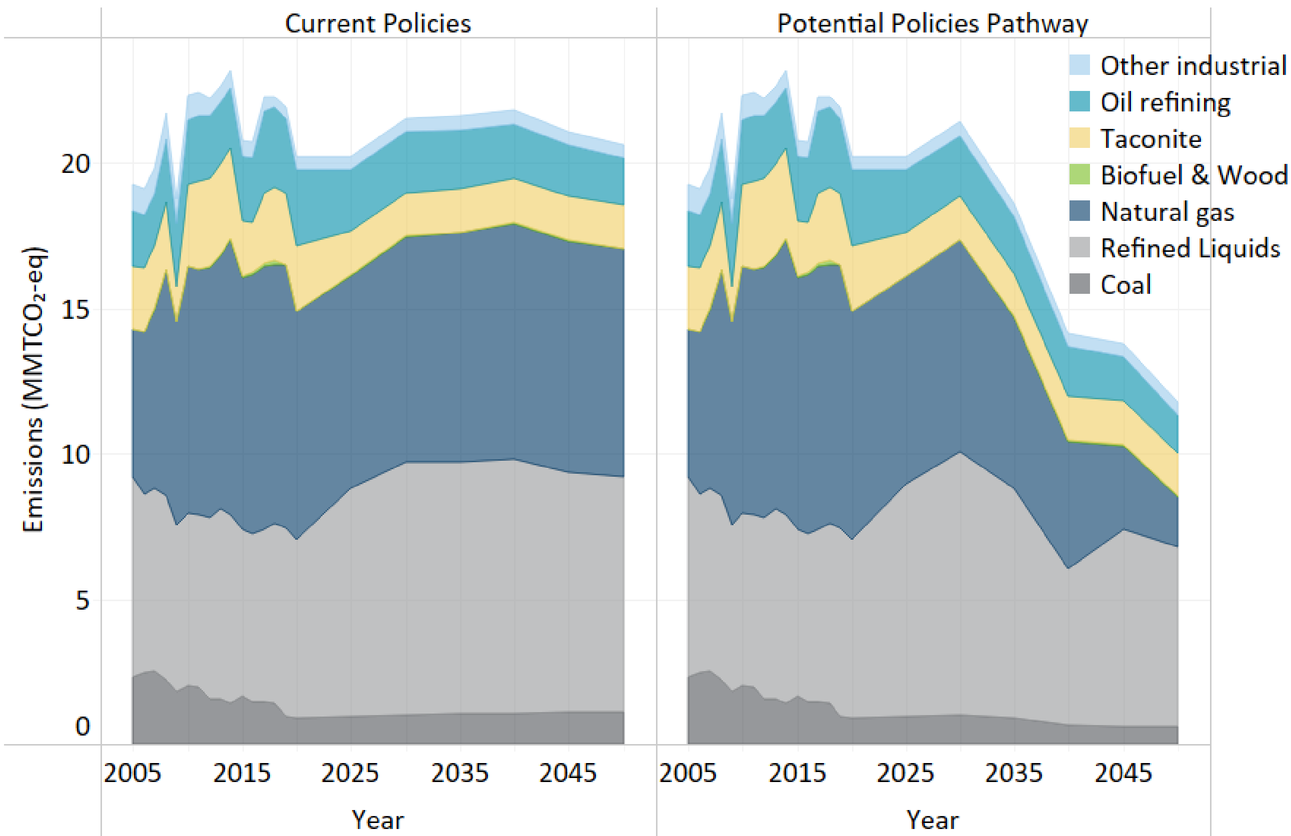
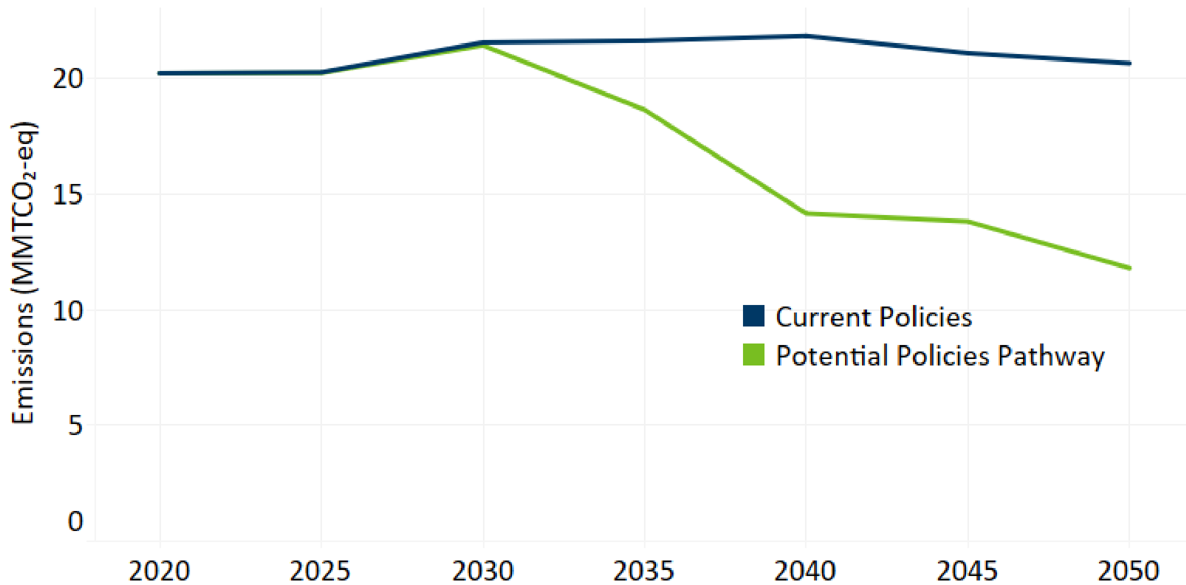
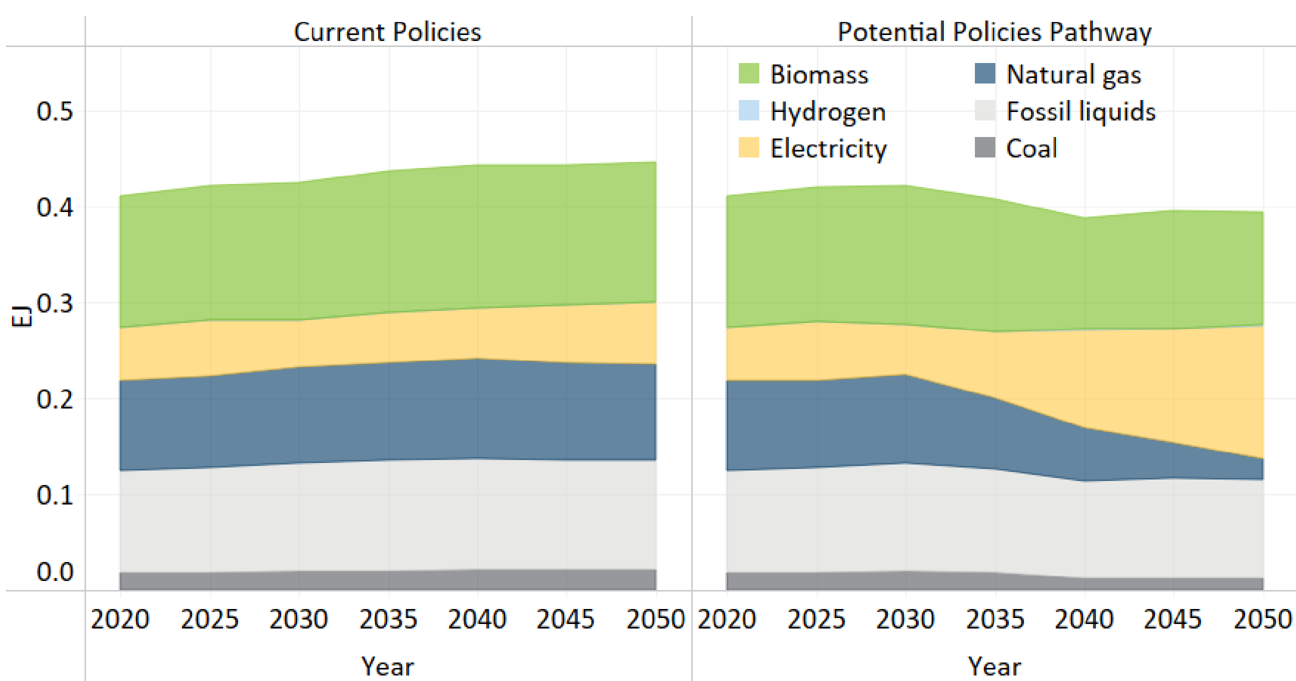


Figure 21. Comparison of projected total industrial sector emissions (MMTCO$_2$-eq) under the Current Policies and Potential Policies Pathway scenarios.



Industrial efficiency standards and a cap-and-invest program were forecast to be effective in reducing natural gas use and increasing electrification, as well as lowering the sector energy demand while allowing for economic growth (Figure 22). Coupled with a Clean Electricity Standard, electrification was forecast to significantly reduce emissions.

Figure 22. Projected energy consumption (EJ) in the industrial sector under the Current Policies and Potential Policies Pathway scenarios.

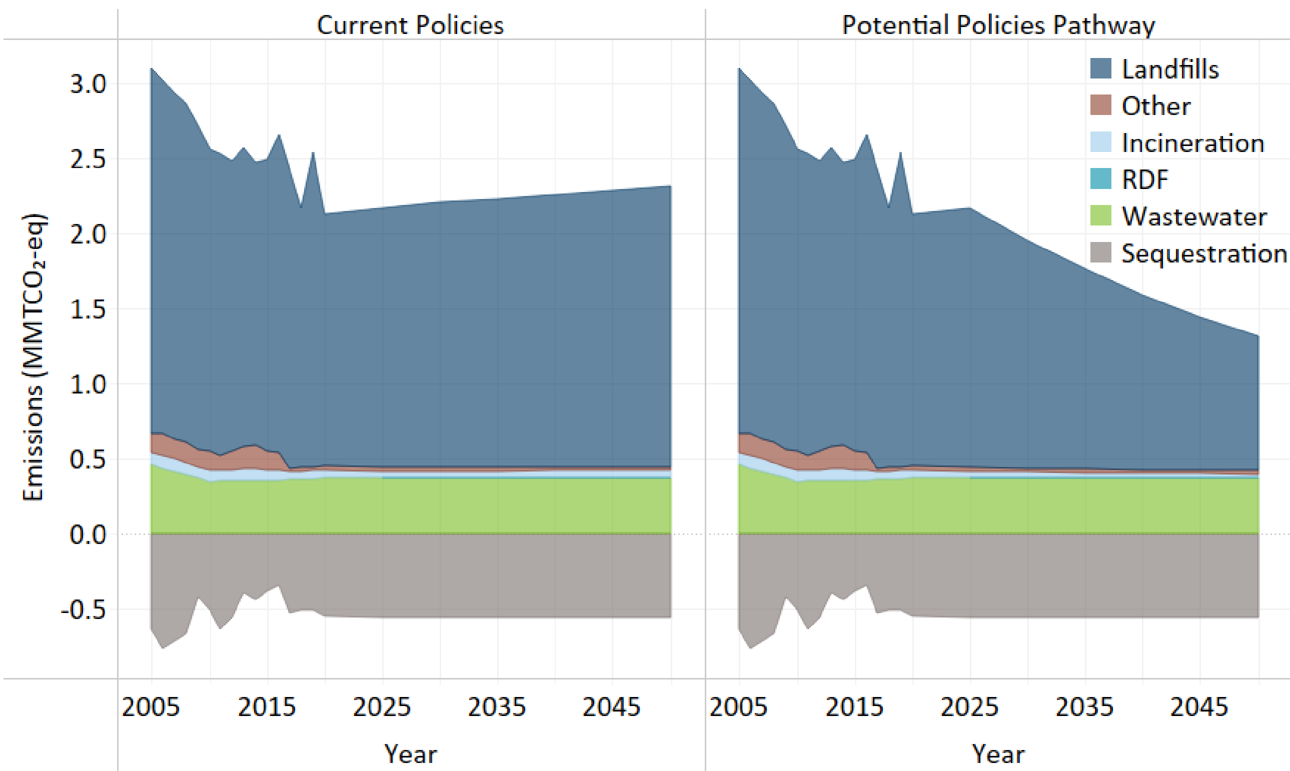


Waste

The waste sector is a small source of emissions compared to other sectors, and steady reductions in emissions have been achieved since 2005. Emissions from the waste sector, particularly landfill emissions, were forecasted to increase slightly under the Current Policies scenario (Figure 23). Sequestration in landfills occurs when wood building materials are placed in demolition and construction landfills, which do not decompose materials like municipal solid waste landfills; this sequestration is variable based on construction and demolition trends, was not modeled, and was held constant at 2020 levels.

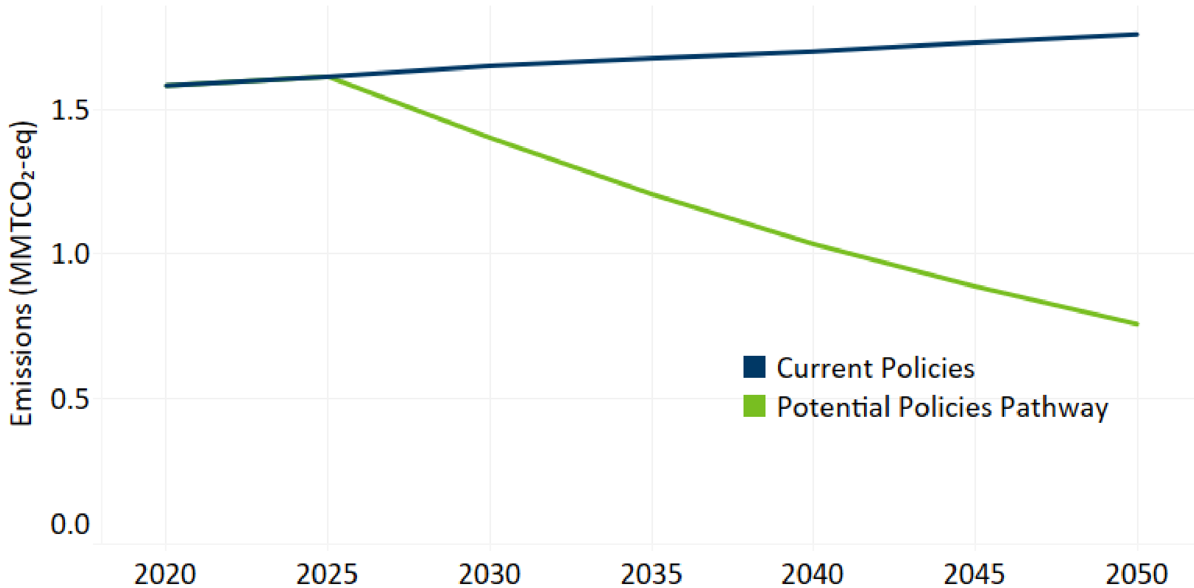
Emissions from the waste sector were forecasted to decrease under the Potential Policies Pathway scenario due to policies addressing landfilled waste (Figure 23). This forecast was not created in GCAM-USA-CGS but was written into the model results as an assumption based on the Metropolitan Solid Waste Management Policy Plan priorities.[111] Emissions from landfilled waste were predicted to decrease as more organic waste is composted and methane capture improves. Emissions in 2050 were approximately 1 $MMTCO_2$-eq lower under the Potential Policies Pathway than under the Current Policies scenario, or about 57% lower (Figure 23).

Figure 23. Waste sector emissions ($MMTCO_2$-eq) under the Current Policies and Potential Policies Pathway scenarios. Projected emissions (2020-2050) were estimated in 5-year increments and calibrated to the historical emissions (2005-2022) at 2020 levels.



[111] MPCA Metropolitan Solid Waste Management Policy Plan 2022-2042 (w-sw7-22) https://www.pca.state.mn.us/sites/default/files/w-sw7-22.pdf

Figure 24. Comparison of total waste sector emissions ($MMTCO_2$-eq) projected under Current Policies and the Potential Policies Pathway scenarios.



Agriculture

Within the agriculture sector, implementation of the Current Policies scenario after federal rollbacks was projected to decrease net emissions by about 0.3 million metric tons of CO_2-eq annually by 2050 relative to a 2005 baseline (Figure 25). Net emissions in 2050 would be approximately 30.7 $MMTCO_2$-eq, representing a reduction of about 0.9% compared to 2005 and 0.2% compared to 2022.

Implementation of the Potential Policies Pathway scenario was projected to reduce agriculture sector emissions by approximately 12.5 million metric tons of CO_2-eq annually by 2050 relative to the Current Policies Scenario (Figure 25, Figure 26). This represents a reduction of about 40% compared to 2005 and 41% compared to 2022. The largest impacts come from additional soil carbon storage, reduction in methane and nitrous oxide emissions from crop and animal agriculture, and reduced carbon losses from drained histosols in crop production due to peatland rewetting. See Figure 27 for the estimated GHG impacts of each agriculture and LULUCF policy from the Potential Policies Pathway scenario (all agriculture and LULUCF strategies are presented together because the GHG impacts of some policies affect multiple sectors due to land use change).

Figure 25. Agriculture sector GHG fluxes under Current Policies (left) and the Potential Policies Pathway (right) scenarios, both with federal rollbacks.

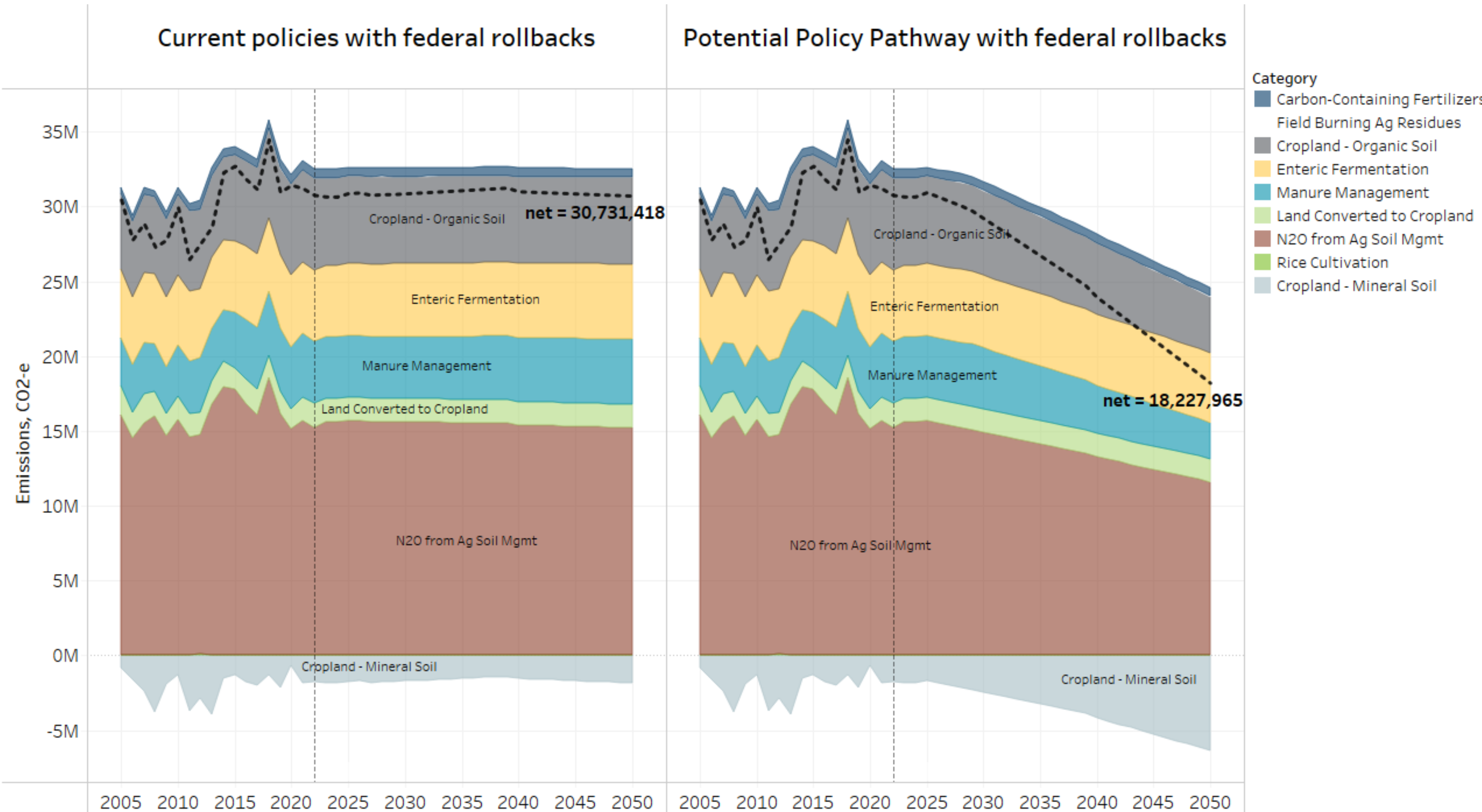


Figure 26. Comparison of agriculture sector policies on net emissions (MMTCO$_2$-eq) under the Current Policies and Potential Policies Pathway scenarios.

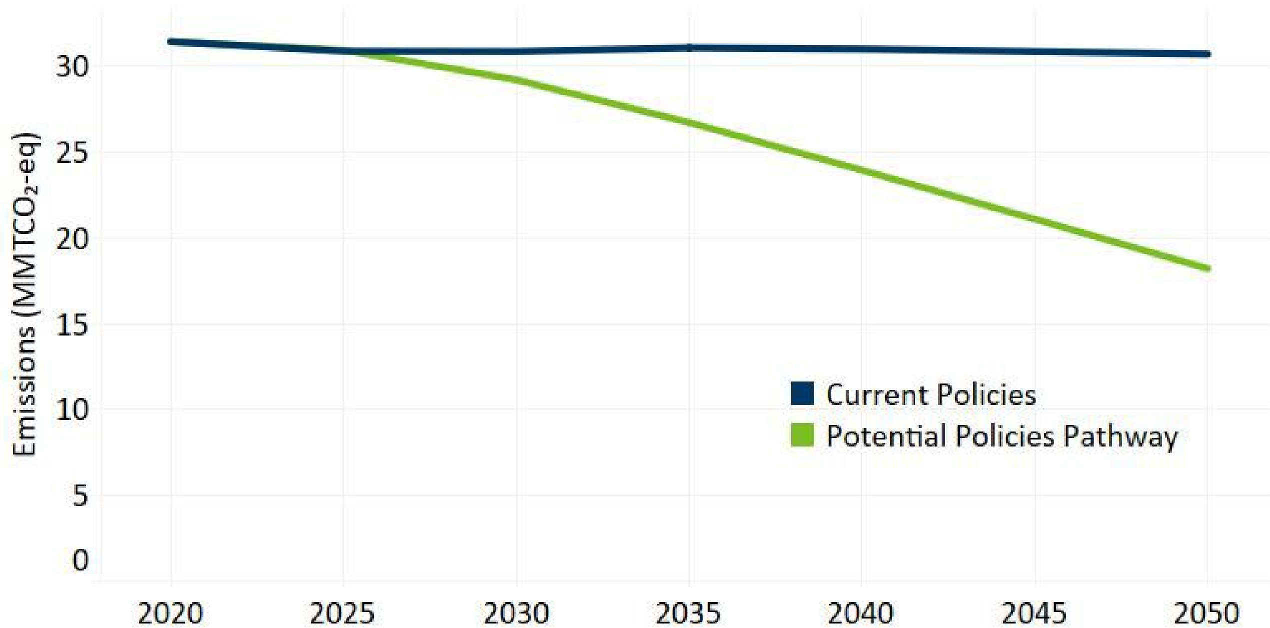
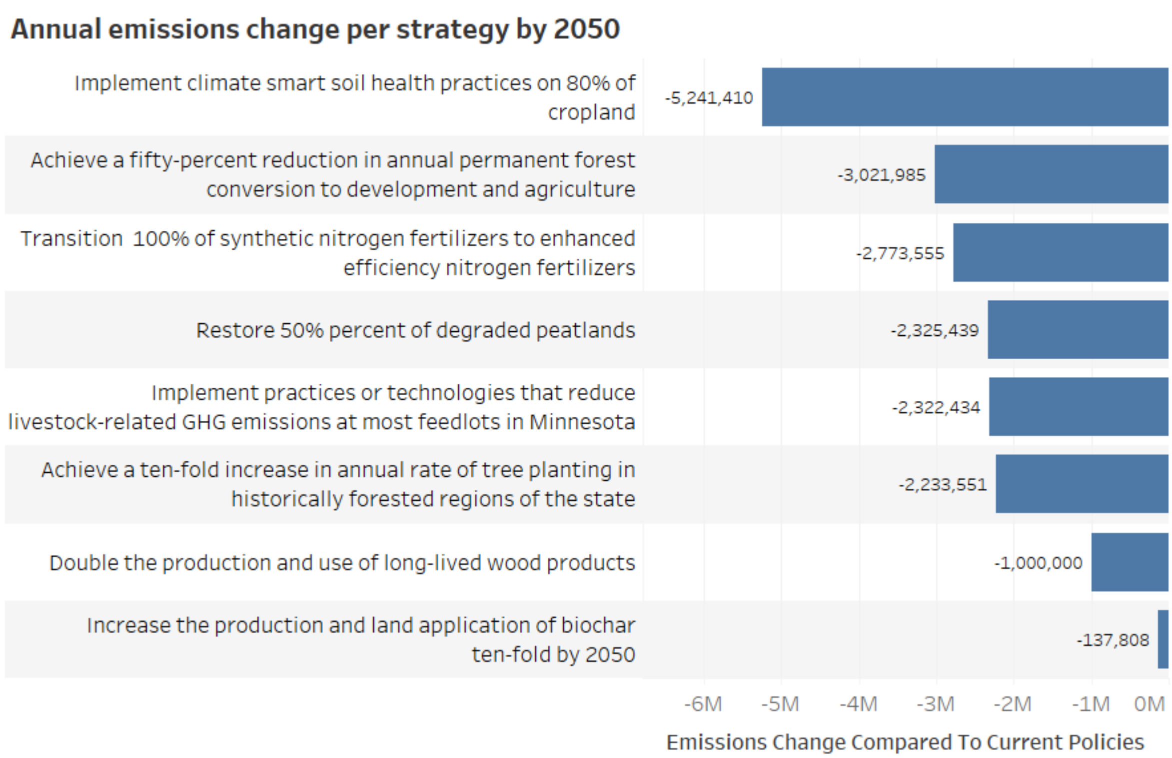


Figure 27. GHG impacts of the policies included in the Potential Policies Pathway scenario within the agriculture and LULUCF sectors, expressed in metric tons.



Land use, land-use change, and forestry

Within the land use, land-use change, and forestry (LULUCF) sector, implementation of current policies is expected to increase net emissions by about 7.0 million metric tons of CO_2-eq annually by 2050 relative to 2005 baseline emissions (Figure 28). Net emissions in 2050 would be approximately -4.6 $MMTCO_2$-eq, which represents a decrease in net sequestration of about 60% compared to 2005 and 66% compared to 2022. LULUCF emissions are not expected to be impacted by federal rollbacks.

Implementation of the Potential Policies Pathway scenario is expected to reduce LULUCF emissions by about 7.5 million metric tons of CO_2-eq annually by 2050 relative to the Current Policies scenario (Figure 28, Figure 29). Despite aging forests and increasing emissions from warming peatlands, the actions in the Potential Policies Pathway scenario are expected to maintain this sector's annual net sequestration at levels similar to those from 2005-2022. See Figure 27 for the estimated GHG impacts of each agriculture and LULUCF policy from the Potential Policies Pathway (all agriculture and LULUCF strategies are presented together because the GHG impacts of some policies affect multiple sectors due to land use change).

Figure 28. Comparison of LULUCF sector policies on net emissions ($MMTCO_2$-eq) under Current Policies and Potential Policies Pathway scenarios.

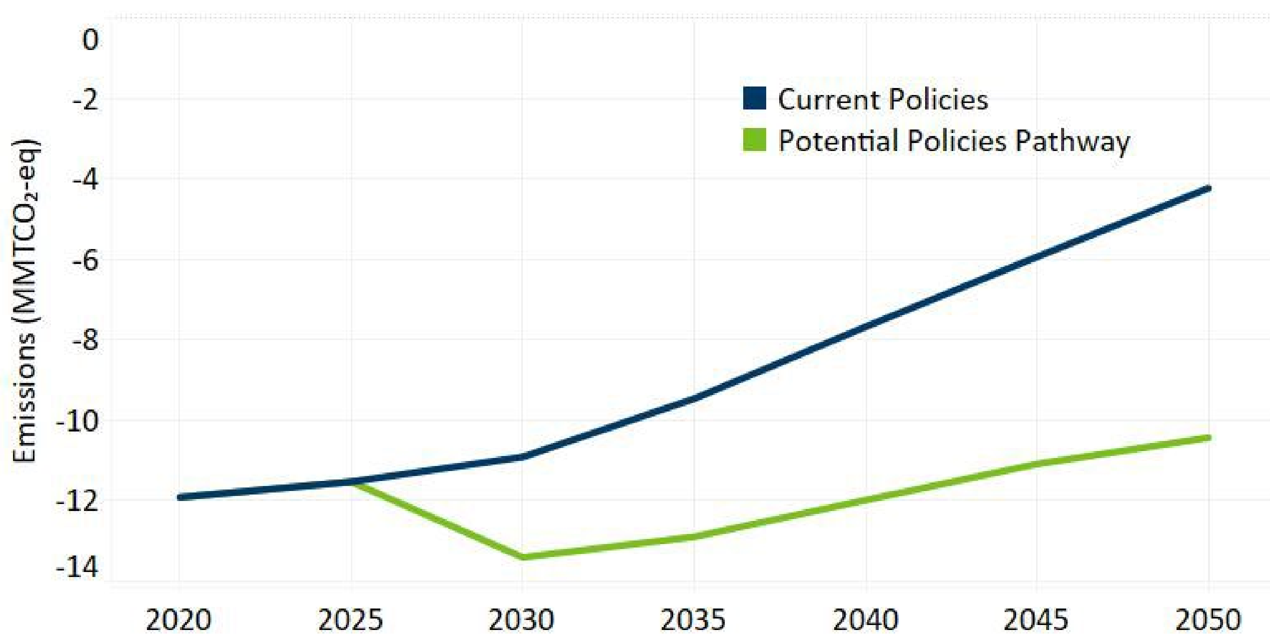
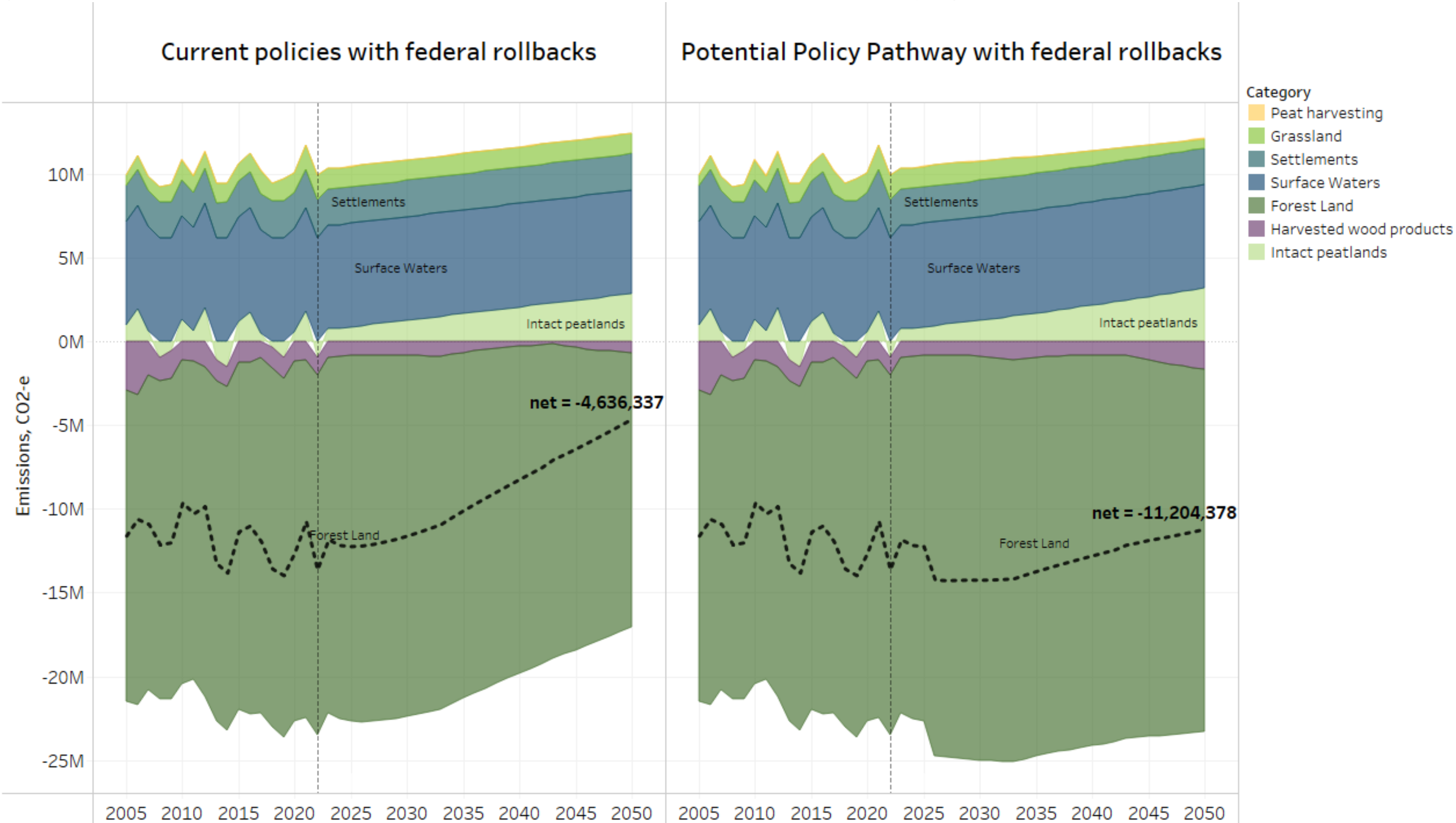


Figure 29. LULUCF sector GHG fluxes under Current Policies (left) and the Potential Policies Pathway (right) scenarios.



Impact of federal rollbacks on the Current Policies and Potential Policies Pathway scenarios

Most federal policies affected by recent rollbacks were intended to incentivize near-term action as part of the Inflation Reduction Act and other near-term standards and regulations. However, the consequences of the federal rollbacks will continue to be felt in the years ahead as current technology remains in use. The impact of the rollbacks is therefore felt more strongly in the near term, and most significantly in the electricity generation, industrial, and transportation sectors (Figure 30, Table 24, Table 25). By 2050, emissions were projected to be only slightly higher because of the rollbacks. However, because the rollbacks were projected to slow emission reductions in Minnesota and across the US, they contribute to higher atmospheric GHG levels for a longer period. Waste and LULUCF were the only sectors where rollbacks were not identified as having an explicit and direct impact, though indirect impacts on land use and management may occur.

Figure 30. Projected total GHG emissions under the Current Policies and Potential Policies Pathway scenarios, before and after federal rollbacks.

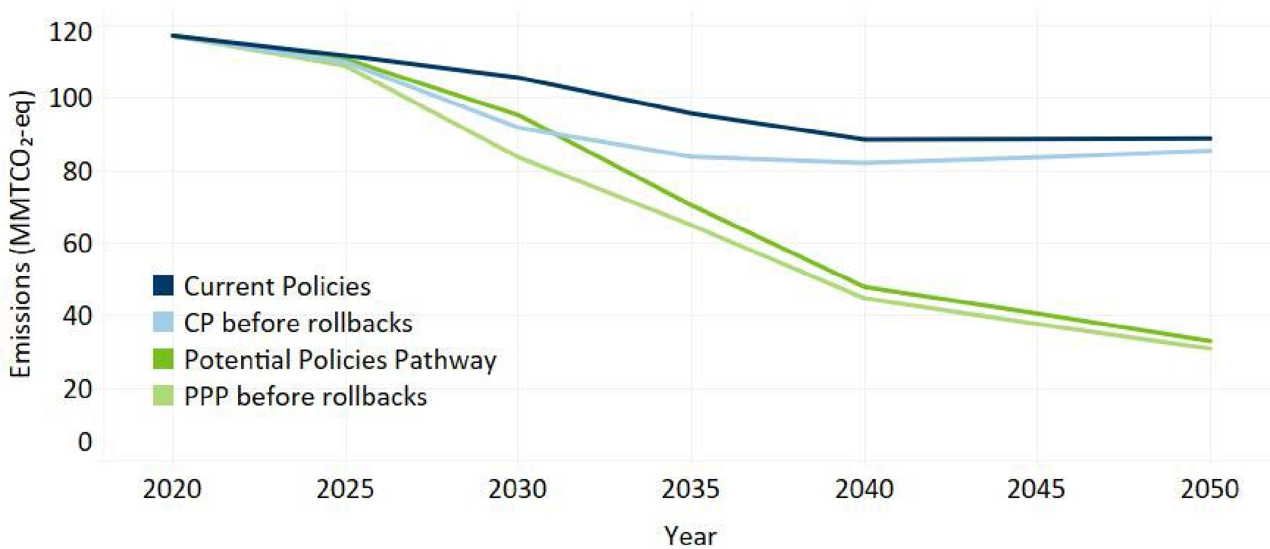


Table 24. Impact of federal rollbacks on the Current Policies (CP) scenario GHG emissions, MMTCO$_2$-eq, in 2030 and 2050 by sector.

Sector	2030 CP Before Federal Rollbacks	2030 CP After Federal Rollbacks	2030 CP Emissions Change	2050 CP Before Federal Rollbacks	2050 CP After Federal Rollbacks	2050 CP Emissions Change
Electricity	8.7	17.5	+8.8	0.2	0.3	+0.1
Transportation	25.7	27.5	+1.8	23.7	24.4	+0.7
Buildings	16.7	17.4	+0.7	14.2	15.3	+1.1
Industry	19.9	21.5	+1.6	20.3	20.6	+0.3
Waste	1.6	1.6	0.0	1.8	1.8	0.0
Agriculture	30.2	30.9	+0.7	29.6	30.7	+1.1
LULUCF	-10.9	-10.9	0.0	-4.2	-4.2	0.0
Net GHG total	91.9	105.7	+13.8	85.5	88.9	+3.4

Table 25. Impact of federal rollbacks on the Potential Policies Pathway (PPP) scenario emissions in 2030 and 2050 by economic sector.

Sector	2030 PPP before rollbacks	2030 PPP after rollbacks	2030 Emissions Change from Federal Rollbacks ($MMTCO_2$-eq)	2050 PPP before rollbacks	2050 PPP after rollbacks	2050 Emissions Change from Federal Rollbacks ($MMTCO_2$-eq)
Electricity	10.0	17.0	+7.0	0.3	0.4	+0.1
Transportation	20.4	22.5	+2.1	3.0	3.4	+0.4
Buildings	16.6	17.2	+0.6	8.8	8.9	+0.1
Industry	20.1	21.4	+1.3	11.3	11.8	+0.5
Waste	1.4	1.4	0.0	0.8	0.8	0.0
Agriculture	28.6	29.2	+0.6	17.2	18.2	+1.0
LULUCF	-13.4	-13.4	0.0	-10.4	-10.4	0.0
Net GHG total	83.7	95.3	+11.6	30.9	33.0	+2.1

Federal policy changes were forecasted to lower electrification rates, thereby reducing forecasted future electricity demand (Figure 31). Transportation electrification was estimated in the forecast to decline significantly after the presumed revocation of federal vehicle emissions standard waivers. Industrial electricity consumption was forecasted to decline in the near term in the absence of incentives. Without federal incentives, the deployment of new renewable generation was forecast to slow in the near term but continue to grow overall due to state policy and electric utility development projections (Figure 32, Figure 33). At the same time, electricity demand from large, emerging loads, such as data centers, was not explicitly forecasted in Minnesota in the modeling framework and remains uncertain; such loads could materially increase electricity demand and potentially outweigh modeled demand reductions depending on siting decisions, technology choices, and market conditions.

Figure 31. Projected electricity consumption (TWh) in buildings, industry, and transportation under the Potential Policies Pathway scenario before and after federal rollbacks.

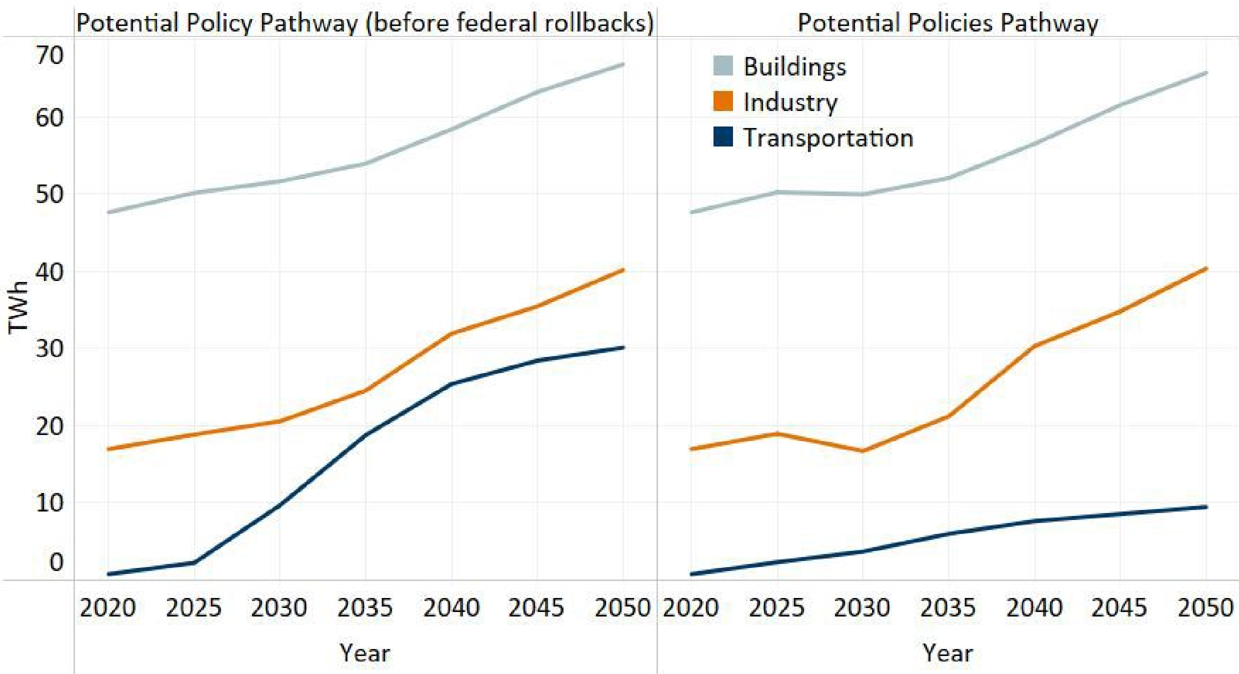


Figure 32. Projected electricity generation (TWh) by energy input under the Potential Policies Pathway scenario before and after federal rollbacks.

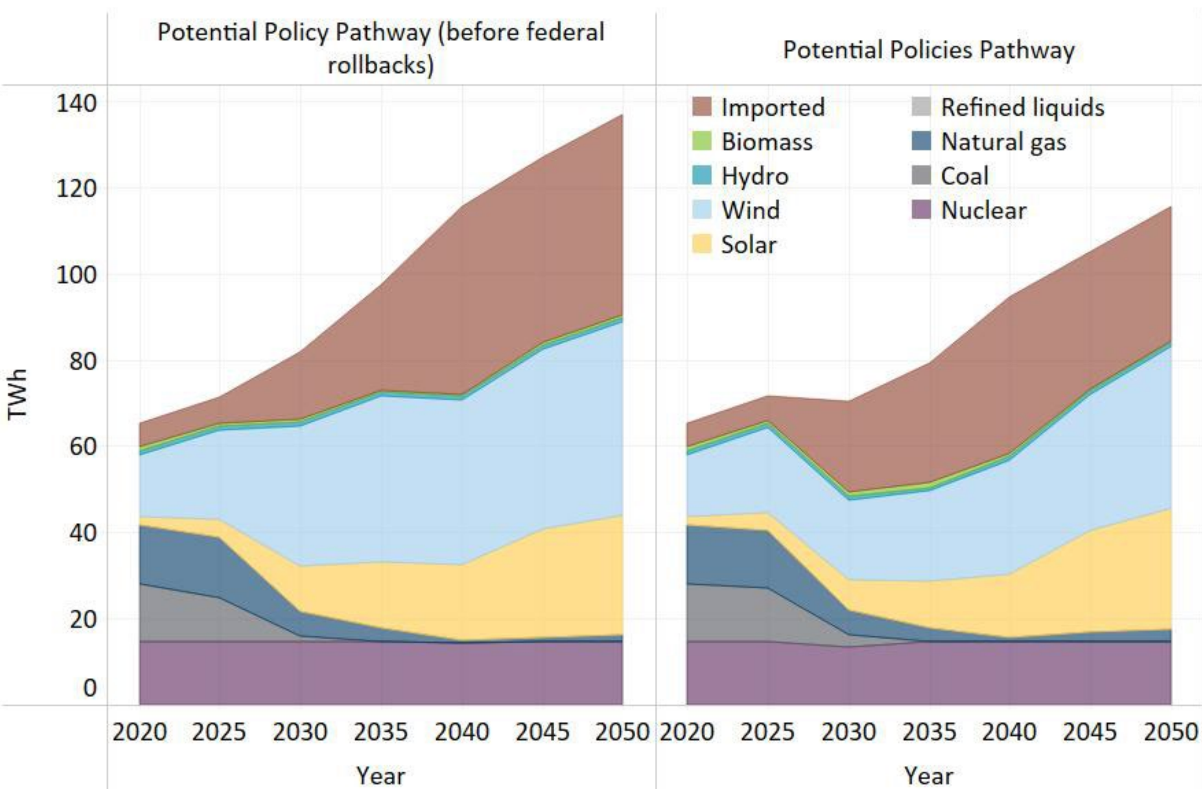
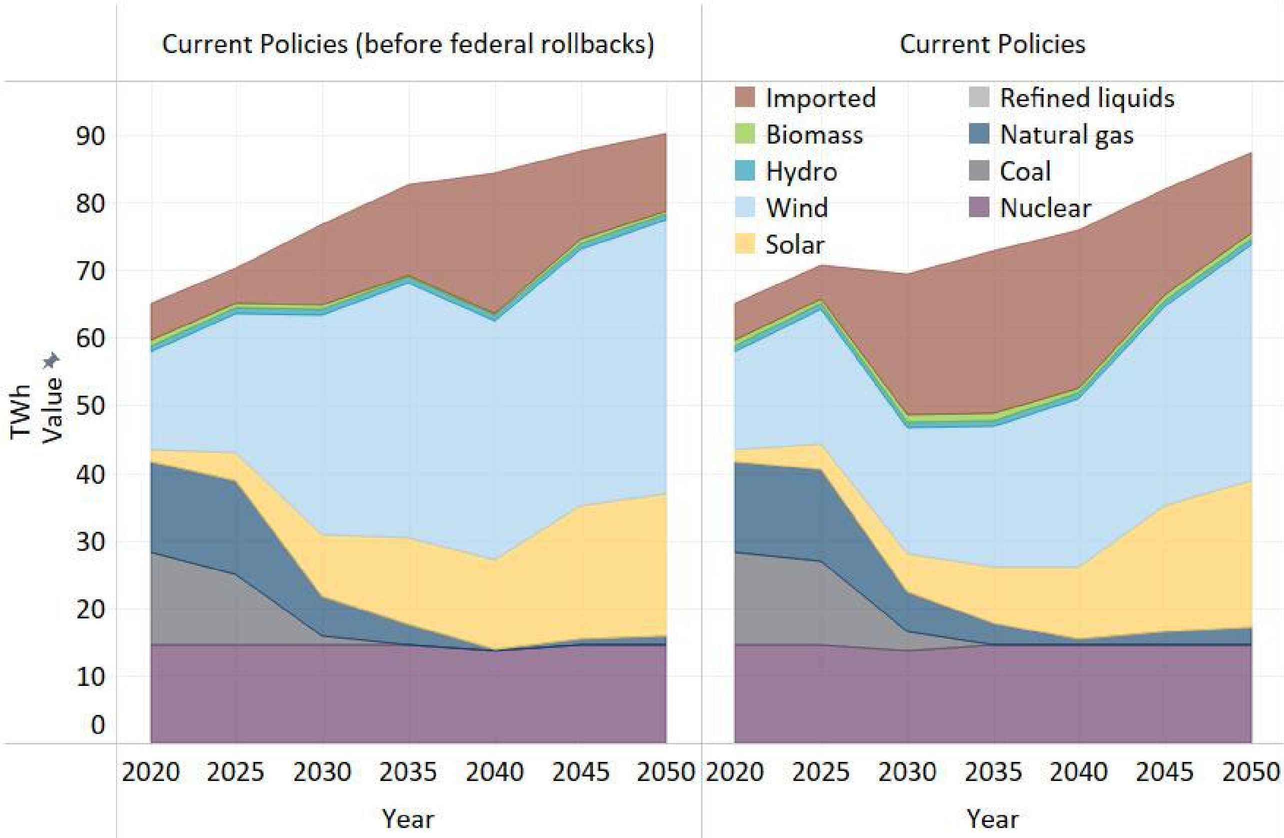


Figure 33. Projected electricity generation (TWh) by energy input under Current Policies scenario before and after federal rollbacks.



Impact of a cap-and-invest policy on the Potential Policies Pathway

A comparison of the Potential Policies Pathway scenario with and without the cap-and-invest policy allows for the analysis of the impact of that policy within the portfolio of other policies. Including the cap-and-invest policy yielded greater GHG emission reductions than the portfolio of potential policies without it (Figure 34, Table 26). Notably, while the cap-and-invest policy was designed to reduce emissions from the largest industrial sources, its flexibility also affected emissions from electricity generation and commercial and residential buildings through investments to reduce emissions in these sectors. In 2050, total emissions were forecast to be 25% lower when a cap-and-invest policy was included.

Figure 34. Projected total GHG emissions under the Potential Policies Pathway scenario, with and without a cap-and-invest policy, by sector.

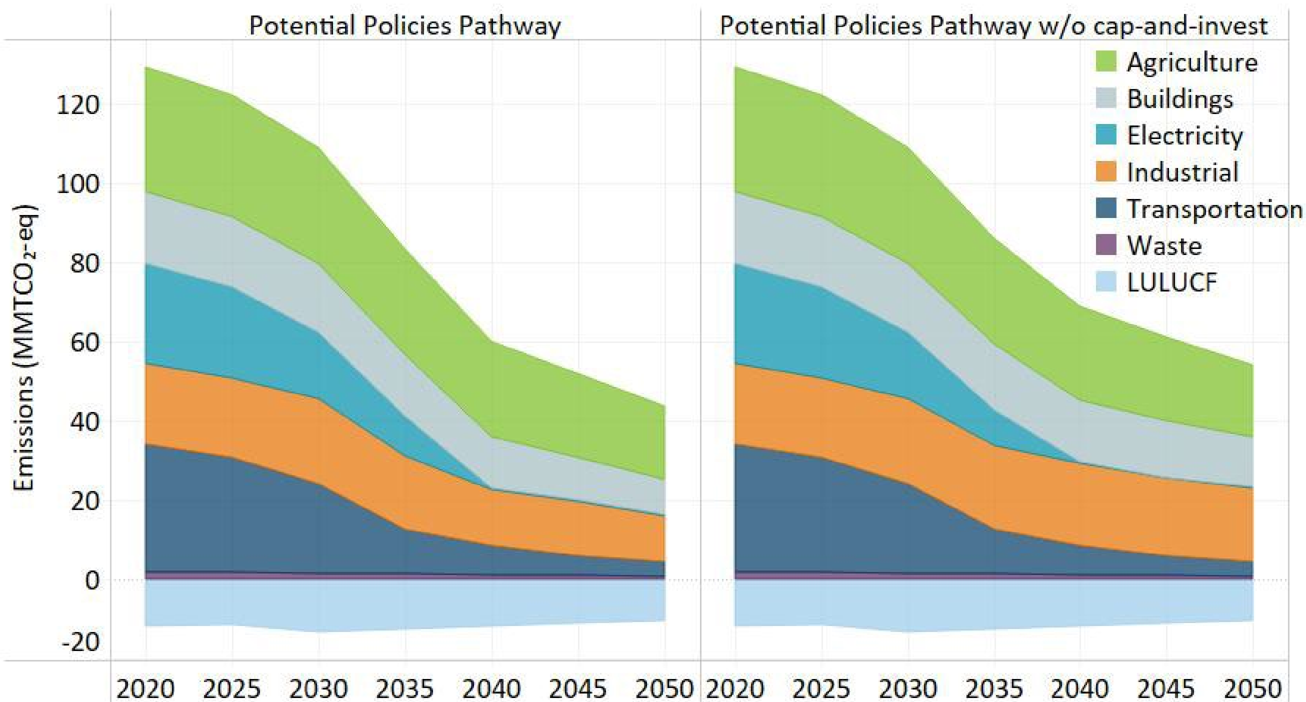


Table 26. Sources of GHG emissions impacted by the cap-and-invest policy under the Potential Policies Pathway scenario with and without the cap-and-invest policy included, and the magnitude of policy impact in MMTCO$_2$-eq, where the change because of policy inclusion was greater than 50,000 MTCO$_2$-eq (0.05 MMTCO$_2$-eq.)

Sector	Source	Potential Policies Pathway scenario				Potential Policies Pathway scenario without cap-and-invest				Change in emissions without cap-and-invest			
		2035	2040	2045	2050	2035	2040	2045	2050	2035	2040	2045	2050
	Coal	0.9	0.7	0.6	0.6	1.1	1.2	1.3	1.3	0.2	0.5	0.6	0.7
	Natural Gas	5.9	4.4	2.8	1.7	6.7	5.7	4.3	3.3	0.8	1.3	1.4	1.6
	Oil Refining	1.9	1.7	1.5	1.3	2.0	1.9	1.7	1.6	0.1	0.2	0.2	0.3
	Refined liquids	7.9	5.4	6.8	6.2	9.5	10.1	10.3	10.5	1.6	4.7	3.5	4.3
Industrial	Subtotal	16.6	12.1	11.8	9.8	19.2	18.8	17.5	16.7	2.6	6.7	5.8	6.9
	Net electricity imports	8.9	0.2	0.2	0.2	7.9	0.1	0.1	0.1	-1.0	-0.1	-0.1	-0.1
Electricity	Subtotal	8.9	0.2	0.2	0.2	7.9	0.1	0.1	0.1	-1.0	-0.1	-0.1	-0.1
	Natural gas	11.6	9.8	7.7	6.3	12.3	11.9	10.9	9.6	0.6	2.0	3.1	3.3
	Refined liquids	2.1	1.7	1.4	1.1	2.3	2.0	1.8	1.5	0.1	0.3	0.4	0.4
Buildings	Subtotal	13.7	11.5	9.1	7.4	14.5	13.9	12.6	11.1	0.8	2.4	3.5	3.7
Total		39.2	23.8	21.1	17.3	41.6	32.8	30.3	27.9	2.4	9.0	9.2	10.5

Net-Zero Pathway scenario

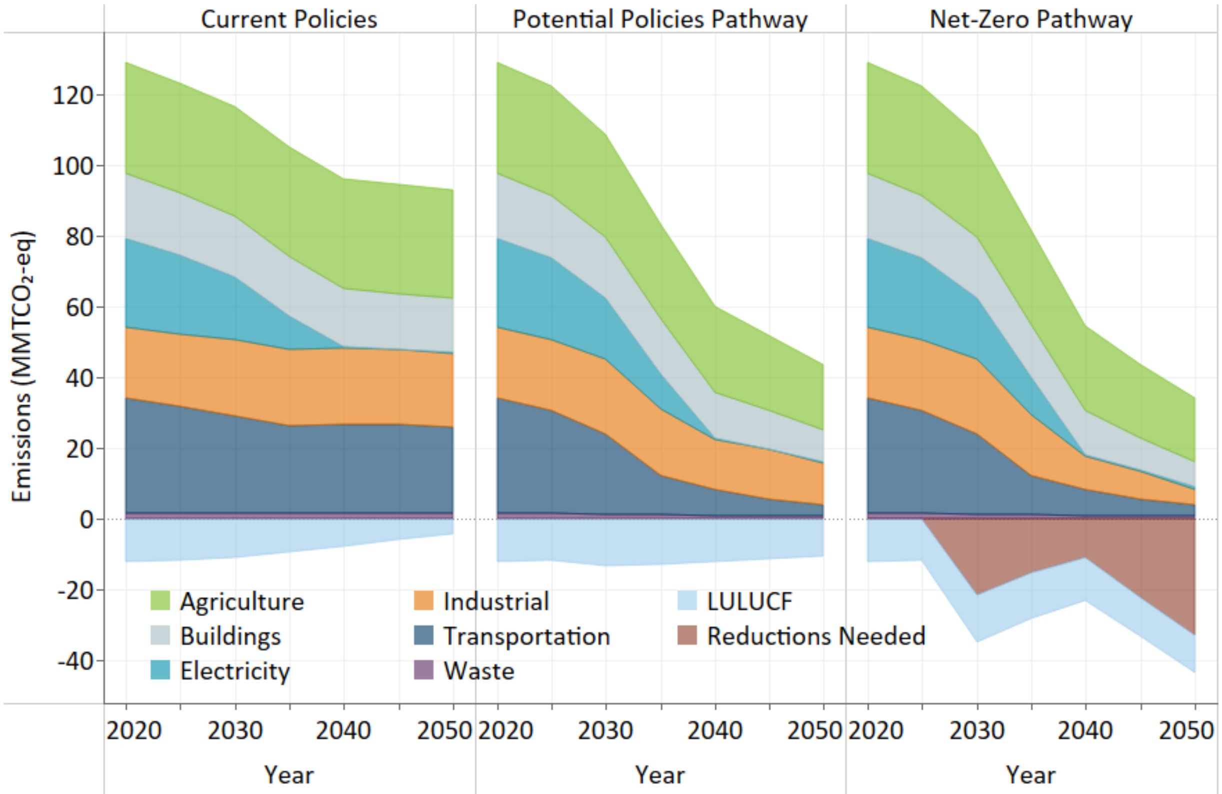
The portfolio of policies analyzed in the Potential Policies Pathway scenario did not achieve the GHG reductions necessary to meet the state's statutory 2030 goal or the 2050 net-zero goal. The Net-Zero Pathway scenario was developed by adding the statutory goals as additional constraints to the Potential Policy Pathway scenario. Comparing the results of the Potential Policies Pathway scenario to the Net-Zero Pathway scenario may help identify additional opportunities to reduce GHG emissions, such as further reductions in natural gas use for buildings and industrial energy or the use of other refined fuels in the industrial sector (Table 27, Figure 35). However, the model was unable to identify emission reductions that would fully achieve the statutory goals, leaving a remaining portion of emissions that could potentially be reduced through carbon capture, technological innovations, or other means.

Table 27. Possible changes in emissions identified by the Net-Zero Pathway scenario to achieve state targets beyond reductions from the Potential Policy Pathway in MMTCO$_2$-eq.

Electricity use increases under the Net-Zero Pathway scenario to replace fossil fuel energy sources, resulting in a slight increase in electricity-sector emissions and larger reductions in emissions from reduced direct fossil fuel use in other sectors. Industrial sector natural gas use also increased in 2035, possibly as a short-term replacement for other fossil fuels. Sources not included in the table remained unchanged between scenarios.

Sector	Source	2030	2035	2040	2045	2050
Commercial and Residential Buildings	Natural gas	0.00	-0.45	-0.79	-1.41	-1.48
	Refined liquids	0.00	-0.10	-0.14	-0.25	-0.34
Electricity	Net electricity imports	0.00	0.65	0.05	0.07	0.08
	Biofuel and wood	0.00	0.00	0.01	0.00	0.00
	Natural gas	0.00	0.00	0.01	0.01	0.01
Industrial	Coal	0.00	-0.07	-0.43	-0.47	-0.55
	Natural gas	0.00	0.05	-1.03	-0.98	-1.37
	Oil refining	0.00	-0.06	-0.13	-0.20	-0.37
	Refined liquids	0.00	-1.51	-2.96	-4.64	-5.17
Subtotal of identified possible additional reductions		0.00	-1.49	-5.41	-7.87	-9.19
Additional emission reductions necessary to reach GHG reduction goals		-22.5	-13.5	-5.57	-14.7	-23.8
Total reductions needed beyond Potential Policy Pathway		-22.5	-15.0	-11.0	-22.7	-33.0

Figure 35. Comparison of projected total GHG emissions under the Current Policies, Potential Policies Pathway, and Net-Zero Pathway scenarios by sector, and additional emission reductions required to meet statutory goals.



Results: Health and economic modeling

COBRA modeling of health impacts

Unless explicitly comparing the impacts of the federal rollbacks, all scenarios refer to versions after accounting for the federal rollbacks.

Comparison of Potential Policies Pathway and Current Policies Pathway

The estimated added health benefits of Minnesota's Potential Policies Pathway scenario, as compared to the Current Policies scenario in 2030 and in 2050, are summarized in Table 28. The largest contributors in terms of monetized benefits across Minnesota were reductions in mortality, asthma incidence and exacerbation of symptoms, and missed school days. In 2030, 94% of the modeled economic value of health benefits came from reductions in early deaths, reflecting the high value of a statistical life. In 2050, nearly 97% of the modeled economic value of health benefits was from reductions in early deaths. Projected reductions in minor restricted activity days had the highest reduction in incidence rate, meaning the benefits will be experienced by the largest number of people. The values in Table 28 represent the estimated number of avoided cases for each adverse health impact and the corresponding monetary savings due to the additional policies in Minnesota's Potential Policies Pathway scenario. While most incidence values represent impacts occurring in 2030 and 2050, respectively, the avoided mortality is over the next 20 years (2030-2050 and 2050-2070, respectively). However, it is important to note that the avoided mortality benefit represents the deaths avoided by lower co-pollutant emissions in a single year, so it should still be considered an annual benefit of lower emissions, not an estimate of benefits over 20 years of lower emissions. For example, in the Potential Policies Pathway scenario, there would be between 86 and 173 early deaths from lower co-pollutant emissions in 2050 and approximately 39 fewer cases of nonfatal heart attacks in 2050. All values in the table are rounded to avoid communicating overprecision in estimation methods.

Table 28. Additional health benefits of Minnesota's Potential Policies Pathway scenario compared to the Current Policies scenario in 2030 and 2050.

Health impact	Health benefits in 2030		Health benefits in 2050	
	Annual incidence	Economic value ($)	Annual incidence	Economic value ($)
Total health benefits – low estimate	-	$61 million	-	$1.17 billion
Total health benefits – high estimate	-	$123 million	-	$2.28 billion
Mortality* – low estimate	4.48	$57 million	86	$1.10 billion
Mortality* – high estimate	9.35	$119 million	173	$2.21 billion
Nonfatal heart attacks	2.14	$157,000	39	$2.86 million
ER visits for respiratory issues	4.75	$6,730	93.5	$132,000
Respiratory hospital admissions	0.56	$11,300	10.3	$206,000
Asthma onsets	19.5	$1.29 million	378	$25.1 million
Asthma symptoms	3,410	$322,000	66,400	$7.64 million
Minor restricted activity days	4,060	$446,000	71,500	$7.86 million
Work loss days	685	$189,000	12,000	$3.32 million
School loss days	590	$873,000	14,100	$20.8 million

*Mortality estimates are over a 20-year period, 2030-2050 for 2030 health benefits and 2050-2070 for 2050 health benefits.

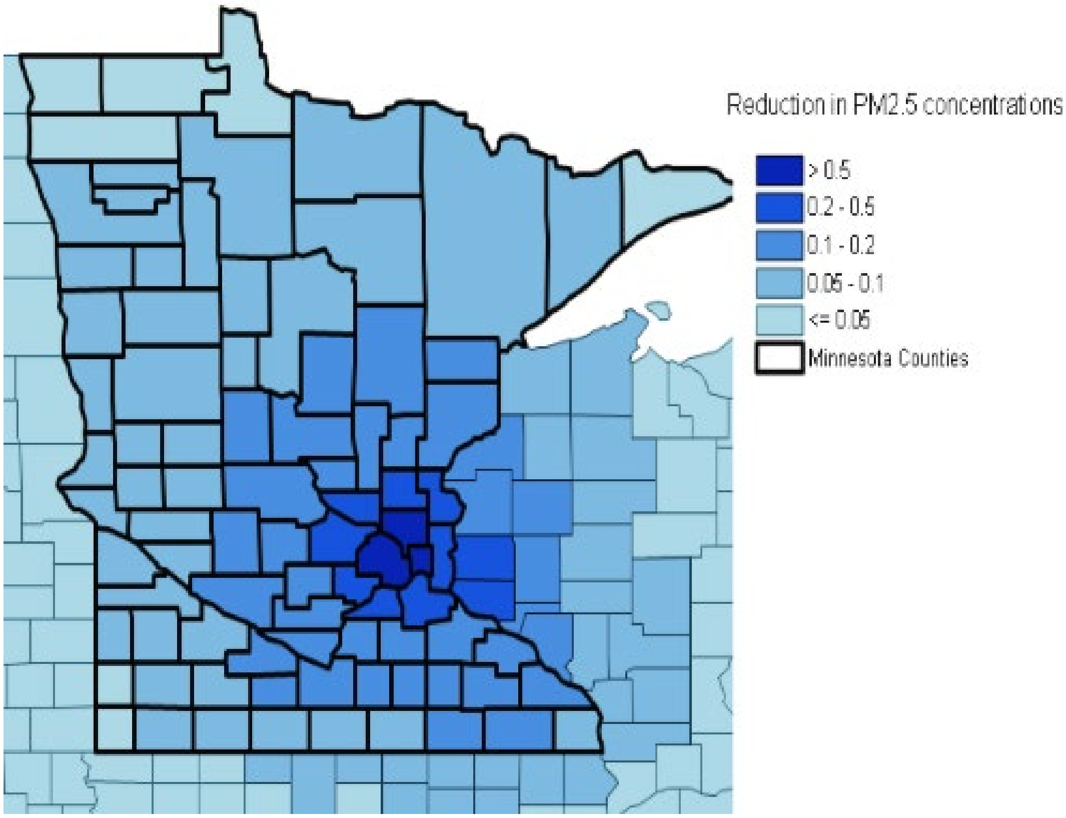
The benefits shown here represent a conservative estimate of health benefits from fully realizing Minnesota's Potential Policies Pathway due to several methodological considerations. The pollutant-change inputs for COBRA were derived from GCAM outputs; therefore, emissions reductions from waste management, agriculture, and land use, land use change, and forestry policies and actions are not included in the COBRA analysis. Further changes in pollutants resulting from policies not included in GCAM modeling would likely yield positive health impacts as well, but they could not be modeled in COBRA. Additionally, the benefits of enacting current policies over halting progress are likely substantial, but they are not represented here because COBRA only captures impacts relative to a baseline (i.e., the Current Policies scenario), not the benefits of the baseline itself. Finally, because COBRA models only the health benefits resulting from improved air quality for $PM_{2.5}$ and ozone, other possible health benefits of the Potential Policies Pathway scenario could not be modeled. Even though quantitative modeling of these additional health benefits is not possible, they are characterized and discussed below.

While the estimates in Table 28 are for all of Minnesota, COBRA estimates changes in health incidence at the county level, allowing an evaluation of the spatial distribution of health benefits. The values in the table were obtained from summing the results for Minnesota's 87 counties to summarize the health benefits for the entire state.

The health benefits of policy action will not be equally distributed across Minnesota due to differences in population density and exposure to pollutant sources. This leads to well-known differences in health outcomes between different communities, with implications for environmental equity. COBRA models $PM_{2.5}$ and ozone concentration changes at the county level to estimate the resulting health outcomes for each county, which allows for a more granular analysis of state-level policies.

Figure 36 shows the modeled reduction of $PM_{2.5}$ concentration (in micrograms per cubic meter) in 2050 in the Potential Policies Pathway scenario relative to the Current Policies scenario in Minnesota counties. For reference, the 2050 COBRA results showed the county-level average concentration of $PM_{2.5}$ to be 4.17 micrograms per cubic meter in the Current Policies scenario and 4.03 micrograms per cubic meter in the Potential Policies Pathway scenario.

Figure 36. Reductions in PM2.5 concentrations (in micrograms per cubic meter) in Minnesota counties in 2050 under the Potential Policies Pathway scenario relative to Current Policies scenario, as modeled by COBRA.



The reductions in $PM_{2.5}$ will tend to cluster in population centers where there are more sources of emissions, with particularly significant benefits accruing to communities in the Twin Cities metro area, which includes many historically disadvantaged communities. This concentration of benefits remains true even when adjusted for population, with total health benefits showing a similar geographical pattern. In 2050, the counties with the largest modeled per capita annual health benefits under the Potential Policies Pathway (based on 2024 county populations) will be Ramsey, Anoka, Hennepin, and Washington counties, all in the Twin Cities metro area. Table 29 shows the 10 counties with the highest per capita health benefits in 2050.

Table 29. Minnesota counties with the highest monetized health benefits in $ per person realized through the additional policies in Minnesota's Potential Policies Pathway scenario compared to Current Policies scenario in 2050. Values are for the high estimate of benefits modeled by COBRA.

Minnesota county	Per capita annual health benefits* ($)
Ramsey	$892
Anoka	$612
Hennepin	$558
Washington	$488
Isanti	$430
Chisago	$399
Mille Lacs	$368
Goodhue	$360
Dakota	$316
Kanabec	$301

*Based on the high estimates for per-county total health benefits

Net-Zero Pathway scenario

There may be even greater health benefits to be realized from climate action in Minnesota. In the Net-Zero Pathway scenario, there are greater reductions in co-pollutant emissions and thus greater potential health benefits than in the Potential Policies Pathway scenario. The Net-Zero Pathway scenario is the modeled pathway of GHG emissions that meets Minnesota's state-wide and sectoral goals to achieve the overall Minnesota goal of net-zero GHG emissions (i.e., carbon neutrality) by 2050.

As in the Potential Policies Pathway scenario, GCAM produced estimates of co-pollutant emissions reductions, and COBRA was used to model the estimated health benefits of the Net-Zero Pathway scenario relative to the Current Policies scenario. Table 30 shows these estimated health benefits resulting from lower co-pollutant emissions in 2050 for both the Potential Policies Pathway and the Net-Zero Pathway scenarios. Both scenarios are compared to the Current Policies scenario, so that the table presents the estimated health benefits achievable by each scenario above and beyond the health benefits realized through Minnesota's current policies.

Table 30. Additional health benefits of Minnesota's Net-Zero Pathway and Potential Policies Pathway scenario, each compared to the Current Policies scenario in 2050.

Health impact	Health benefits in 2050 in Net-Zero Pathway		Health benefits in 2050 in Potential Policies Pathway	
	Annual incidence	Economic value ($)	Annual incidence	Economic value ($)
Total health benefits - low estimate	-	$1.92 billion	-	$1.17 billion
Total health benefits - high estimate	-	$3.73 billion	-	$2.28 billion
Mortality* - low estimate	141	$1.80 billion	86	$1.10 billion
Mortality*- high estimate	283	$3.61 billion	173	$2.21 billion
Nonfatal heart attacks	63	$4.64 million	39	$2.86 million
ER visits for respiratory issues	155	$219,000	93.5	$132,000
Respiratory hospital admissions	16.8	$336,000	10.3	$206,000
Asthma onsets	622	$41.4 million	378	$25.1 million
Asthma symptoms	110,000	$13.0 million	66,400	$7.64 million
Minor restricted activity days	116,000	$12.7 million	71,500	$7.86 million
Work loss days	19,500	$5.38 million	12,000	$3.32 million
School loss days	24,000	$35.5 million	14,100	$20.8 million

*Mortality estimates are over a 20-year period, 2050-2070.

As the table shows, the Net-Zero Pathway scenario estimated health benefits from lower co-pollutant emissions total $1.92 to $3.73 billion relative to the Current Policies scenario, far greater than the $1.17-$2.28 estimated health benefits in the Potential Policies Pathway scenario relative to the Current Policies scenario. In the Net-Zero Pathway scenario, an estimated 141 to 283 early deaths could be avoided from lower co-pollutant emissions in 2050.

The distribution of health benefits across Minnesota in the Net-Zero Pathway scenario was similar to that in the Potential Policies Pathway scenario presented above, with the highest benefits in higher-population areas where emissions tend to be highest, especially the Twin Cities metro area.

Health impacts of federal rollbacks

COBRA modeling of the estimated health benefits of the Potential Policies Pathway before the federal rollbacks scenario, compared to the Potential Policies Pathway after the federal rollbacks, showed that the federal rollbacks will result in significant harm to Minnesotans' health. For example, in 2050, the Potential Policies Pathway before federal rollbacks scenario showed total modeled annual monetized health benefits to be $125 million to $160 million higher than in the Potential Policies Pathway after federal rollbacks scenario. These include between 8 and 11 fewer annual early deaths and up to hundreds and even thousands fewer less-severe health impacts.

Health impacts of the Minnesota cap-and-invest policy

COBRA modeling of the estimated health benefits of the Potential Policies Pathway with and without the cap-and-invest policy showed that the cap-and-invest policy produced significant health benefits in addition to the large GHG emissions reductions shown above. In 2050, the reduction in modeled annual monetized health benefits from removing the cap-and-invest policy was between $830 million and $1.6 billion. These included 61 to 123 more annual early deaths when cap-and-invest is removed from the suite of policies. Considering the total estimated annual health benefits of the Potential Policies Pathway scenario compared to the Current Policies scenario in 2050 ($1.17 billion to $2.28 billion total monetized benefits as seen in Table 30), the cap-and-invest policy not only led to significantly lower GHG emissions but also large health co-benefits from reductions in co-pollutant emissions.

Economic indicators

Unless explicitly comparing the impacts of the federal rollbacks, all scenarios refer to versions after accounting for the federal rollbacks.

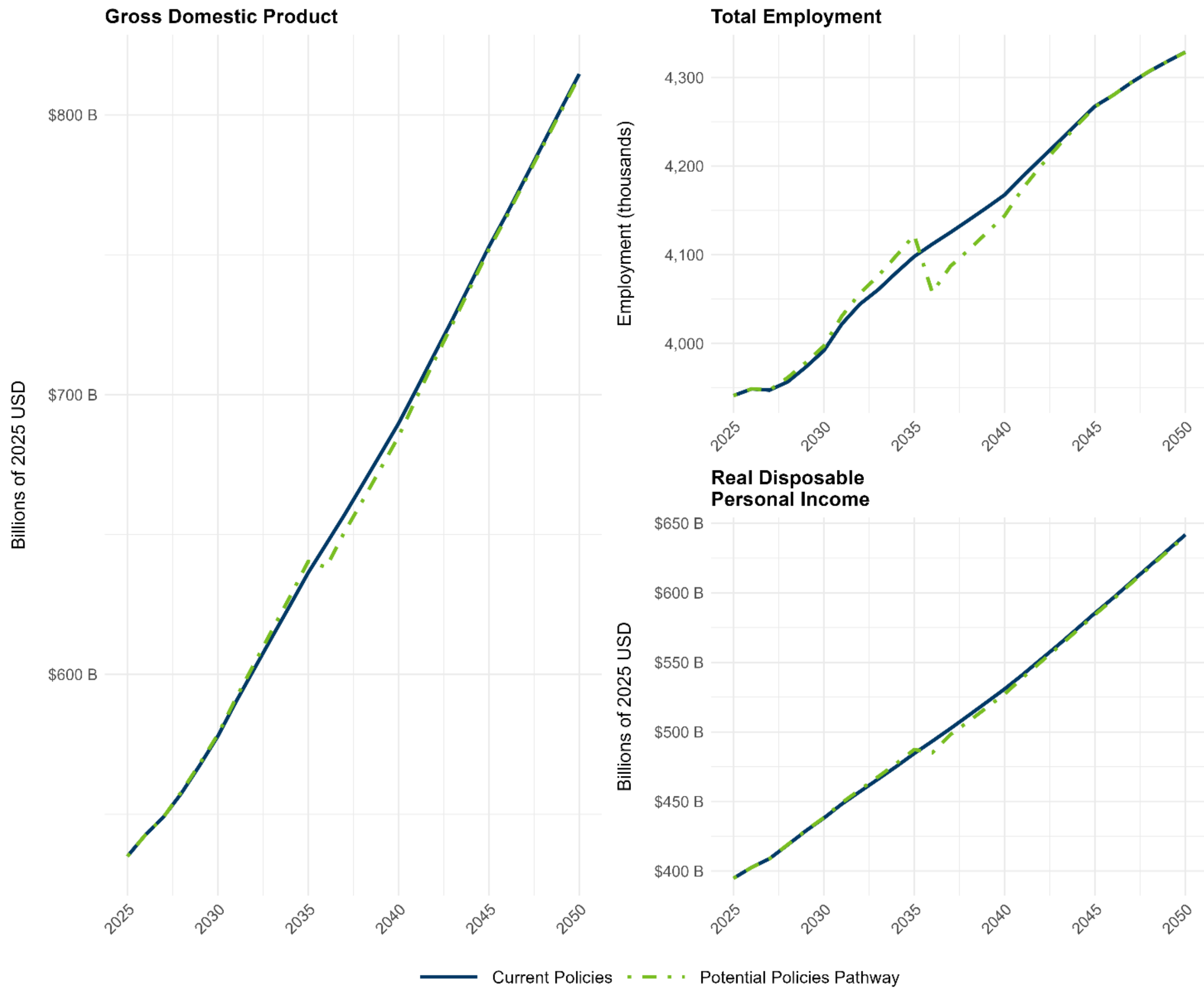
Statewide economic indicators

The main difference between the Current Policies and Potential Policy Pathway scenarios was the timing and type of investment (e.g., electricity- or natural gas-related investments). These timing differences were evident in the trajectories of gross domestic product (GDP), employment, and income. Figure 37 shows statewide trends in GDP, total employment,[112] and real disposable personal income[113] under the Current Policies and Potential Policies Pathway scenarios. Overall economic growth was strong in both cases, with statewide GDP and income increasing steadily through 2050. In aggregate, differences between scenarios were minor, reflecting that both included continued clean-energy and efficiency investments and similar long-term productivity gains.

[112] Base employment in REMI PI+ is larger than base employment used in state employment projections, so absolute employment numbers are not directly comparable with other state reports. For more comparable information on employment projections, employment impacts from modeled current policies, and workforce needs, see the forthcoming workforce document

[113] Disposable income is the amount of money households have left to spend or save after paying taxes. It represents the total take-home income available for everyday expenses, savings, and discretionary purchases.

Figure 37. Statewide economic indicator trends by scenario.



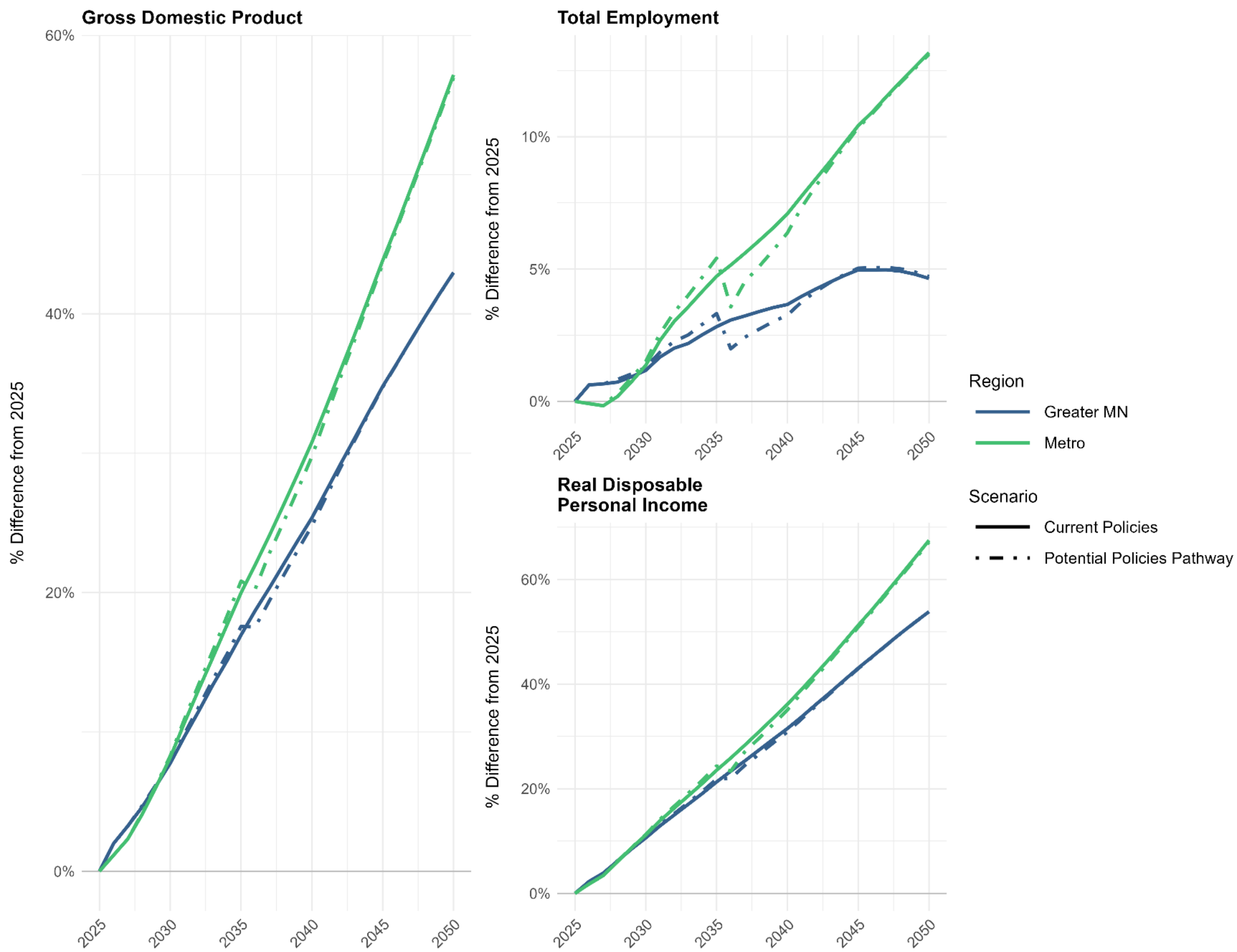
Under the Potential Policy Pathway scenario, modeled industrial investment was more variable, with distinct peaks around 2030 and 2040 and sustained higher spending after 2040 relative to the Current Policies scenario. After 2035, the modeled commercial sector investment accelerated more in the Potential Policy Pathway scenario, which helped smooth out aggregate investment and economy-wide GDP and employment trends. While the modeled transportation investment was low, transportation businesses saw the greatest investment after 2035 in both scenarios.

This led to a brief, small decline in modeled GDP and disposable income in the Potential Policy Pathway scenario around 2035, as near-term industrial investment paused before accelerating again alongside increases in commercial investment. Modeled employment followed a similar pattern—peaking early as near-term construction and retrofit activity ramped up, dipping during the mid-2030s, and then recovering to align with the Current Policies scenario trajectory by 2050.

Regional economic indicators

Figure 38 shows changes in modeled GDP, total employment, and real disposable personal income split by the Twin Cities metro area and Greater Minnesota regions, expressed as percent differences from 2025 levels. Overall, the direction of regional patterns mirrors the statewide trends—both regions experienced steady growth under the Current Policies and Potential Policies Pathway scenarios.

Figure 38. Regional economic indicator trends by scenario, percent change from 2025 levels.



In the near term, Greater Minnesota will see slightly faster GDP, employment, and income growth as construction activity expands to meet early clean-energy and infrastructure investments. Beginning around 2030, the metro area region's growth will accelerate, reflecting increased investment in commercial buildings, industrial decarbonization, and transportation-related industries.

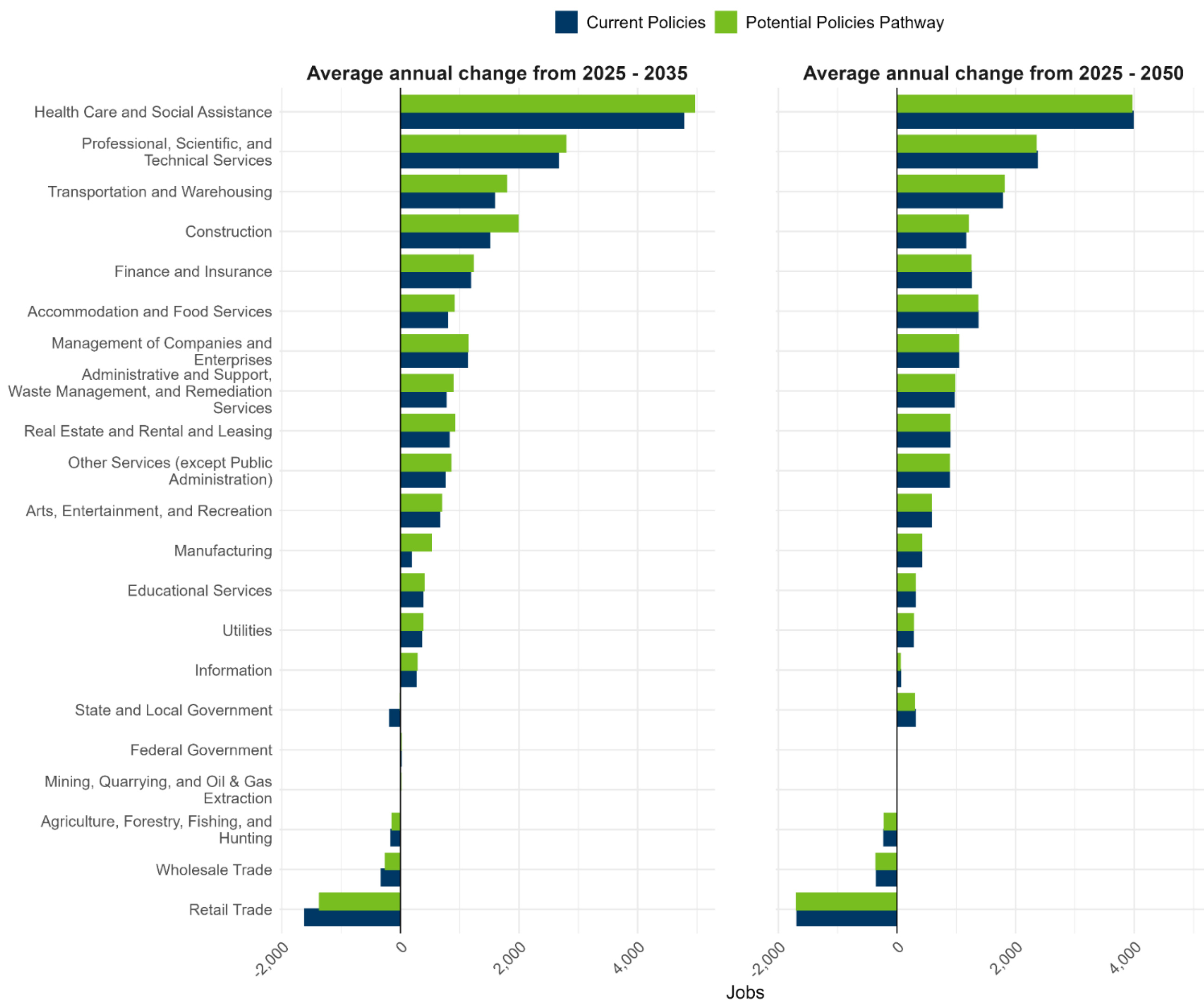
Real disposable personal income will also diverge after 2030, with the metro area region realizing slightly larger cumulative gains through 2050. This reflects differences in the composition of employment and investment—more high-wage service and technology-oriented jobs in the metro area compared with utility and construction industries in Greater Minnesota. Overall, the results indicate that both regions will benefit from sustained economic expansion under both policy scenarios, with only modest differences in timing and income composition.

Employment impacts

Overall modeled employment growth patterns were broadly similar across scenarios, with the Potential Policy Pathway scenario generating slightly larger near- and mid-term gains and smaller losses across all industries. Figure 39 shows the average annual change in employment by industry, comparing Current Policies and Potential Policies Pathway scenarios for the 2025–2035 and 2025–2050 periods.

During the first decade (2025–2035), the construction, professional and technical services, and utilities sectors will see the largest increases in mid-term employment gains relative to long-term growth as investment and clean-energy deployment ramp up. These gains will be more moderate in the longer term (2025–2050), as construction and equipment installation give way to lower-intensity operations and maintenance activities. By 2050, modeled employment levels converge across scenarios, indicating that the main effect of additional policy investment is to shift the timing of job creation rather than substantially change total long-term employment.

Figure 39. Average annual mid-term and long-term statewide industry employment gains by scenario.

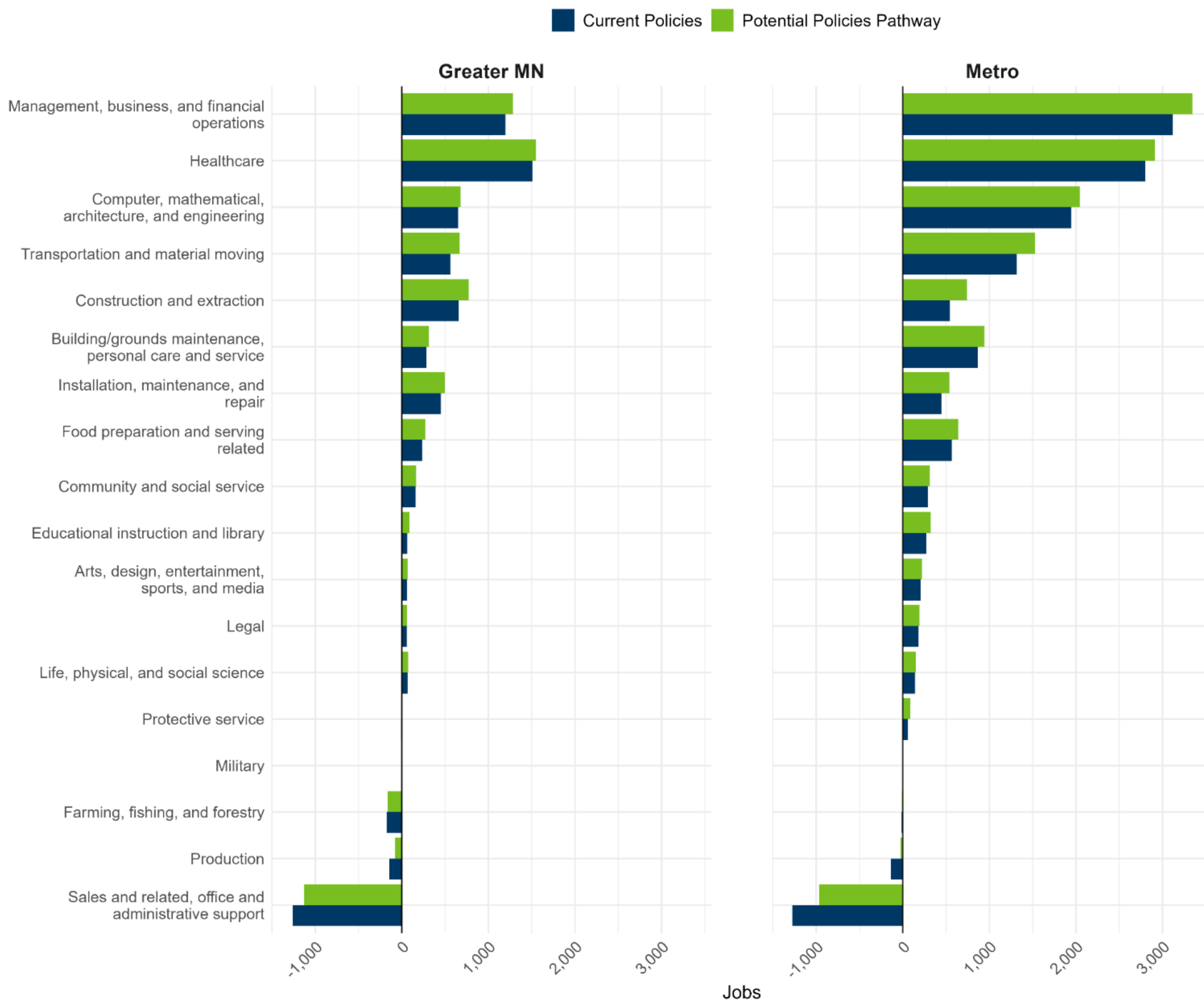


As with statewide industry employment, the Potential Policies Pathway scenario shows slightly larger modeled job gains—or smaller losses—than the Current Policies scenario across all occupations. Figure 40 shows projected average annual changes in employment by major occupational group for Greater Minnesota and the metro area region between 2025 and 2035.

Currently, employment in the metro area region accounts for about 60% of statewide employment, and employment projections indicate that share will increase over time. The modeled scenarios estimated that

66% of state employment will be in the metro area region by 2050. As a result, the metro area will add or retain a greater number of jobs than Greater Minnesota, with three notable exceptions: the professional, technical, and service employment sectors. Greater Minnesota will add a similar number of construction and installation, maintenance, and repair occupations — jobs essential to meeting clean energy deployment and building efficiency needs. These occupations will experience stronger relative growth in Greater Minnesota, which reinforces the importance of statewide workforce readiness for skilled trades and technical roles.

Figure 40. Average annual mid-term occupation employment gains by region and scenario.



Impact of federal rollbacks

Federal rollbacks were projected to increase energy spending in Minnesota, particularly in the near and medium term. Because many rescinded federal incentives were designed to accelerate early adoption of clean technologies, their removal slows electrification and efficiency improvements. As a result, households and businesses will face higher energy costs than they would have under earlier federal policies, with the largest impacts occurring in the buildings and transportation sectors and slightly greater relative impacts on lower- and middle-income households.

The rollbacks also alter investment patterns by delaying the transition toward lower-cost clean technologies. Higher fuel and electricity prices contribute to increased energy costs in some sectors, and slower deployment of efficient or electric alternatives raises operating costs over time. Although the long-term economic trajectory remains positive, the rollbacks modestly reduce near-term economic efficiency by increasing energy expenditures and shifting investment toward costlier, fossil-dependent technologies.

Potential Policies Pathway without a cap-and-invest policy compared to the Potential Policies Pathway

Total energy and capital expenditures were modeled to be broadly similar with and without a cap-and-invest policy (Figure 41). Capital investment will be slightly higher in the cap-and-invest scenario, even before accounting for the reinvestment of auction revenues. While overall spending levels will be comparable, the composition of investment differed: cap-and-invest leads to greater deployment of cleaner technologies, whereas excluding it leads to more fossil-fuel investment.

Differences in modeled statewide economic indicators were minimal: employment, GDP, and disposable personal income are all slightly higher over the mid-term, 2025-2035, when cap-and-invest was included (Figure 41). Over the longer term, the version without cap-and-invest shows marginally higher values, but all differences remain minimal—less than 0.25%. These findings suggest that including cap-and-invest can deliver deeper emissions reductions with negligible overall economic tradeoffs, while shaping a cleaner long-term energy investment profile.

Figure 41. Total energy and capital expenditures under the Potential Policies Pathway scenario, with and without a cap-and-invest policy.

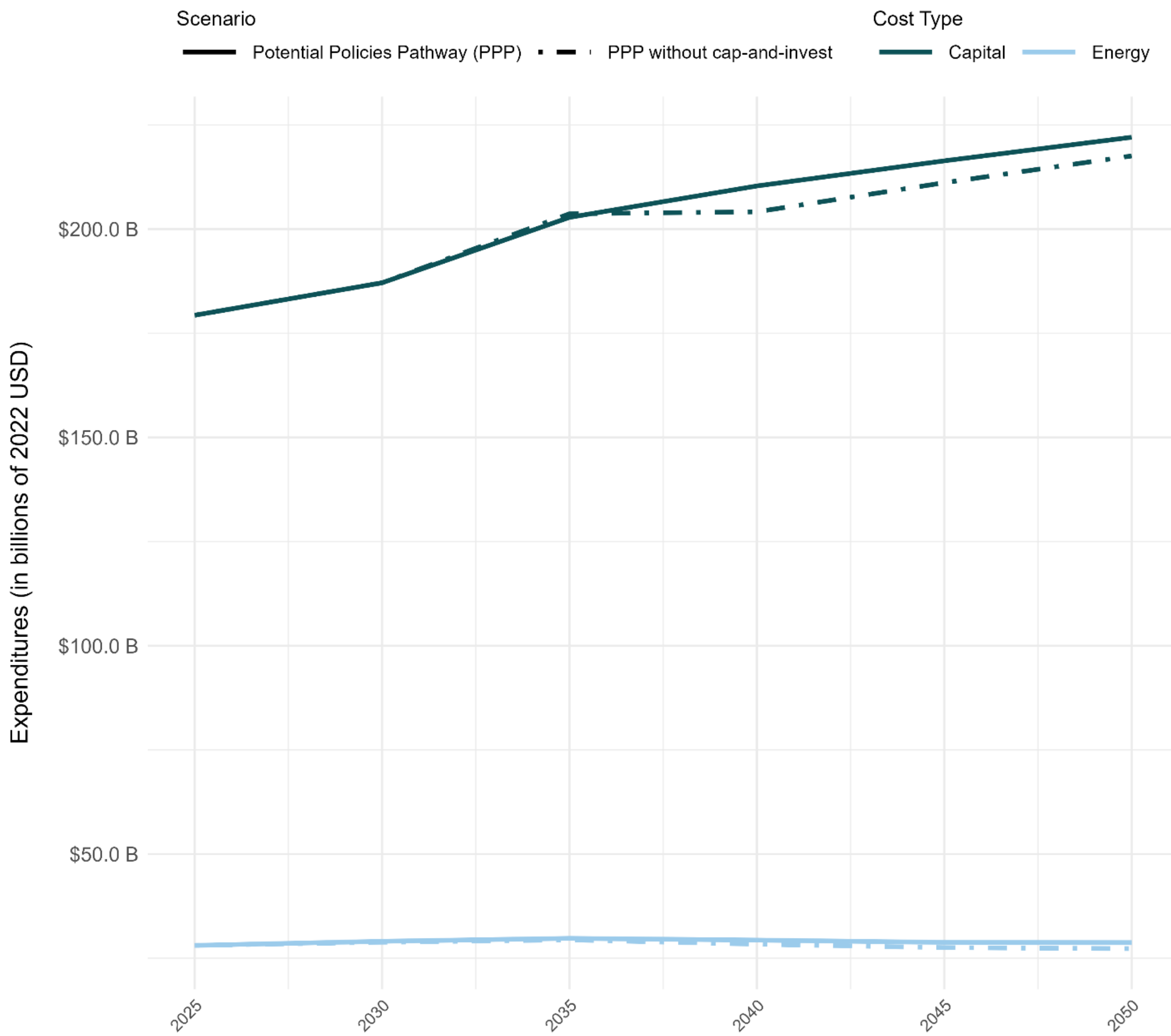
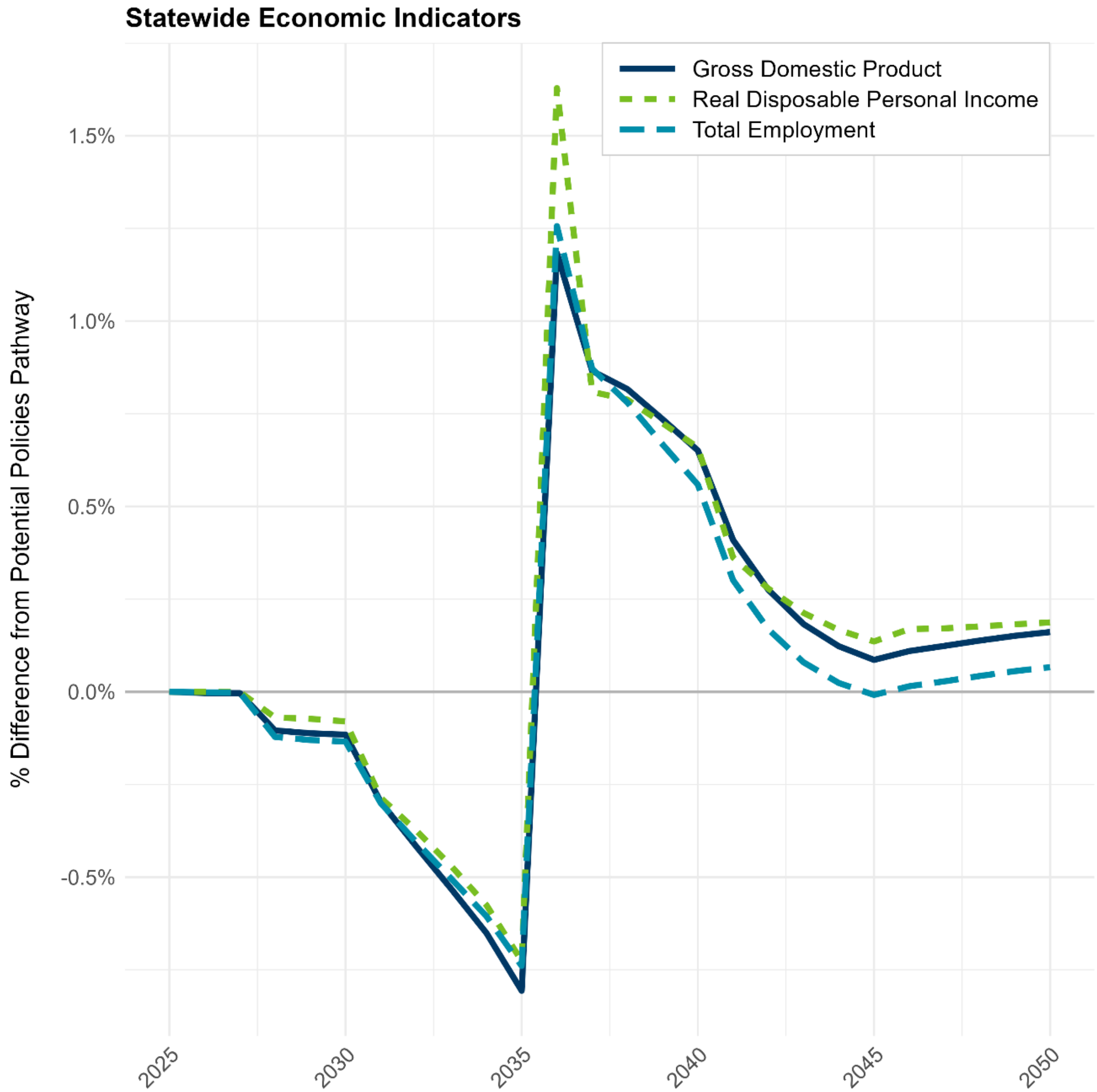


Figure 42: Statewide economic indicator trends, percent difference between the Potential Policies Pathway scenario with and without a cap-and-invest policy.



Net-Zero Pathway compared to the Potential Policies Pathway

The Net-Zero Pathway and the Potential Policies Pathway scenarios track closely through 2035, after which the investment in clean energy, electrification, and other mitigation measures in the Net-Zero Pathway scenario increased beyond the Potential Policies Pathway scenario to drive deeper emissions reductions. This additional investment will come almost exclusively from the commercial and industrial sectors. As shown in the left panel of Figure 43, this increased investment is gradual but sustained—except for a temporary dip between 2035 and 2040, which reflects deferred industrial investment.

Statewide economic indicators remain closely aligned across both scenarios. As shown in Figure 44, GDP, disposable income, and employment are all slightly higher under the Net-Zero Pathway scenario in the long term. However, the differences are minor—none exceed 1% over the modeling horizon.

Figure 43. Total energy and capital expenditures under the Potential Policies Pathway and Net-Zero Pathway scenarios.

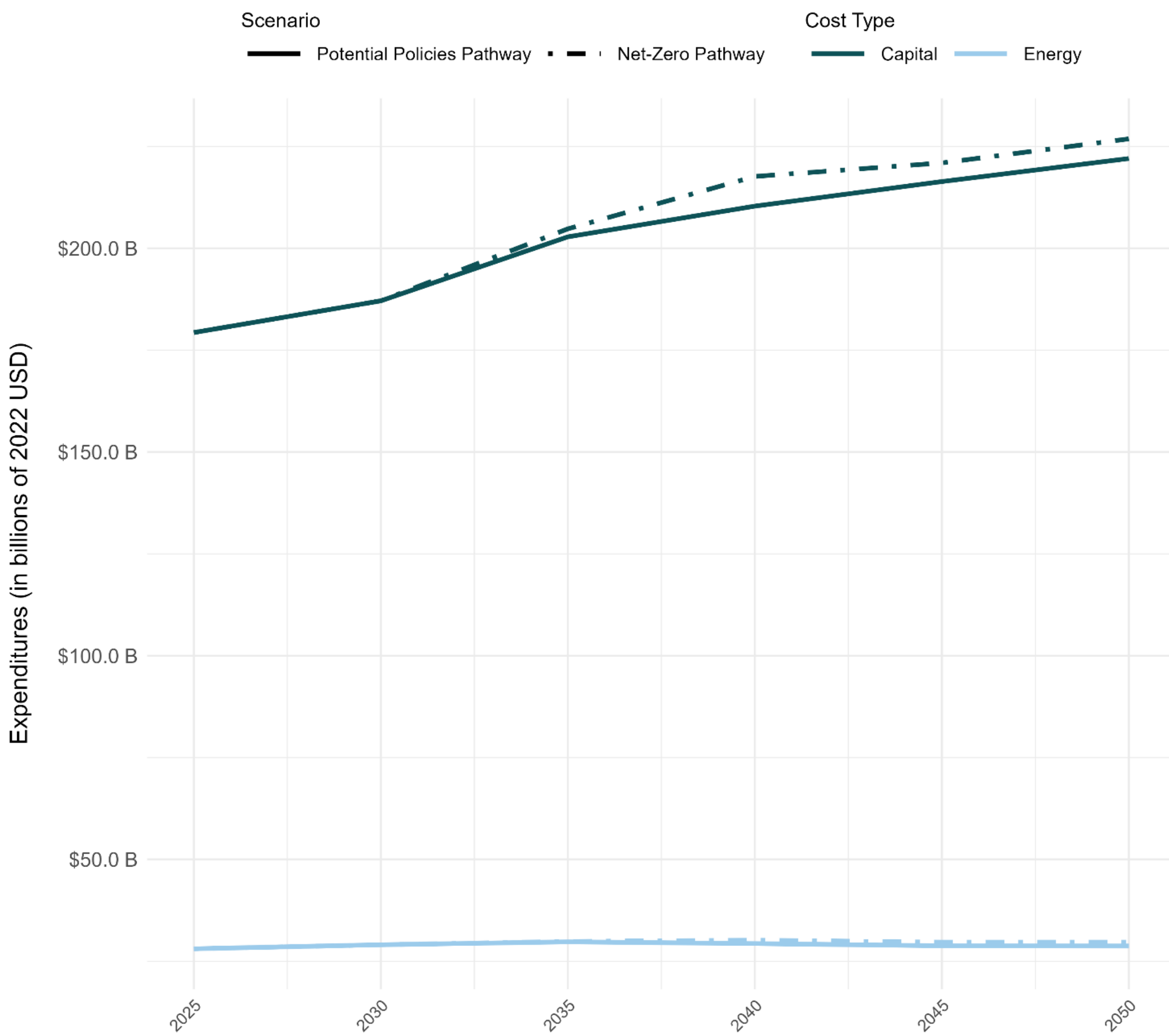
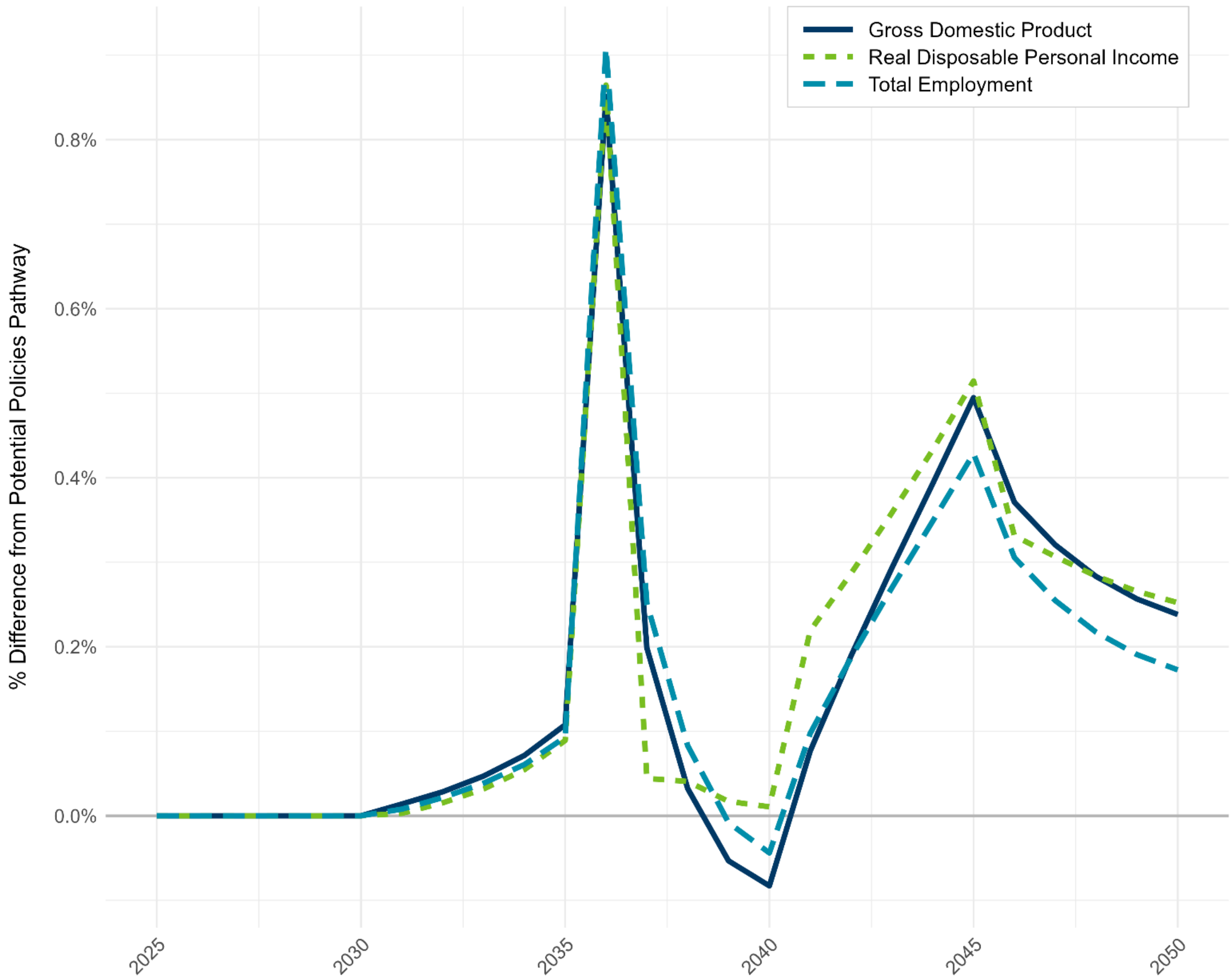


Figure 44: Statewide economic indicator trends, percent difference between the Potential Policies Pathway and Net-Zero Pathway scenarios.



Appendix A: Core GCAM assumptions

The results of this study depended on many assumptions about how Minnesota might evolve in the future. This study used a set of core assumptions for drivers, including economic growth, population growth, coal power retirement, nuclear power retainment, and energy demands reflecting economic impacts associated with COVID-19 in 2020 and subsequent recovery (Supplementary Table A1). The core assumptions drew from a set of data sources referenced in the main report and other parts of this technical appendix, for example, EIA's *Annual Energy Outlook*[114] and Rhodium Group.[115]

Supplementary Table A1. Core assumptions for Minnesota

Drivers	Scenario assumptions
Economic growth	GDP growth trajectories established in the open-source release of GCAM-USA v7.3 are employed for these scenarios. Overall GDP increases approximately by 2% annually from 2020 to 2050. GDP is one of the primary drivers of overall demand growth in all sectors of the economy, which has a direct impact on emissions.
Population growth	Population growth is assumed to be approximately 0.4% per year on average from 2020 to 2050 for these scenarios. Population is one of the primary drivers of overall demand growth in all sectors of the economy, which has a direct impact on emissions.
Retirement of coal-fired power plants	All existing coal-fired power plants are assumed to retire by 2035. Announced retirement dates were collected from Global Energy Monitor's Global Coal Plant Tracker.[116] The retirement of coal power plants impacts fossil fuel emissions in the electricity sector and the need for new electric generation capacity.
Transportation energy demand	Transport sector energy demand decreases by 12.6% from 2015 levels in 2020 to represent the COVID-19 pandemic, with recovery through 2025. This directly impacts emissions in the transportation sector.
Industrial energy demand	Industry sector energy demand decreases by 4.1% from 2015 levels in 2020, with recovery through 2025. This directly impacts emissions in the industry sector. The growth rate of industrial energy consumption in Minnesota was recalibrated to match Annual Energy Outlook (AEO) projections for Energy Consumption of Industrial sector for West North Central region.[117] Specifically, energy consumption in 2050 is modeled to be approximately 1.25x industrial energy consumed in 2020. The output for total final energy of industry was calibrated to the AEO projects detailed above.
Technology Costs	Technology costs are updated with NREL Annual Technology Baseline 2022 assumptions.[118]

[114] U.S. Energy Information Administration. Annual Energy Outlook 2022. EIA. https://www.eia.gov/outlooks/archive/aeo22/ (accessed 2023-06-23).

[115] Larsen, K.; Pitt, H.; Larsen, J.; Herndon, W.; Houser, T.; Kolus, H.; Mohan, S.; Wimberger, E. Taking Stock 2020: The COVID-19 Edition; Rhodium Group, 2020. https://rhg.com/wp-content/uploads/2020/07/Taking-Stock-2020-The-COVID-19-Edition.pdf (accessed 2023-06-23).

[116] Global Coal Plant Tracker. Global Energy Monitor. https://globalenergymonitor.org/projects/global-coal-plant-tracker/ (accessed July 2024).

[117] Energy Information Administration. U.S. Energy Information Administration (EIA), Short-Term Energy Outlook, November 2022 and EIA, AEO2023, 2022.

[118] NREL (National Renewable Energy Laboratory). 2022 Annual Technology Baseline; Golden, CO, 2022. https://atb.nrel.gov/.

Appendix B: Policy representations in GCAM scenario design

Model parameters described in the following tables were designed to represent the current and potential policies and may have impacts that reach beyond targeted sectors and interact with other policies.

Supplementary Table B1. Representation of policies for cap-and-invest in GCAM-USA-CGS.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Minnesota	Cap and invest	Not modeled in this scenario.	The Minnesota cap-and-invest policy is designed to follow a specific trajectory for covered emissions. The cap covers approximately 10% of statewide emissions and is primarily focused on the largest emitters, though it exempts electric utilities and taconite mining. While primarily addressing industrial emitters, the cap-and-invest program is designed to allow both the industry and building sectors to address emission-reduction potential at the least cost. In practice, such a design may represent emissions reductions in the buildings sector that can be traded as credits to industrial facilities covered under the cap-and-invest program. The program is modeled to begin in 2030 and steadily decrease the emissions cap through 2050. The policy is intended to reach a 45% reduction 10 years after the program starts relative to the 2005 baseline, and approximately 78% reduction in 2050.

Supplementary Table B2. Representation of electricity sector policies in GCAM-USA-CGS.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Minnesota	Renewable/clean energy targets	A Clean Electricity Standard (CES) with a 100% target in 2040 is modeled. This policy was implemented by setting a minimum % of total electricity load to be met by zero/low-emissions sources of generation, including renewable energy, nuclear, and biomass. This standard was also assumed to apply to emissions from imported electricity and, therefore, includes states in the MISO North Grid Region through mechanisms such as PPAs and time-matched renewable energy certificates (RECs).	Same as in Current Policies scenario.
	Coal power retirement	We assume the achievement of all planned and announced retirements of coal-fired power plants in Minnesota. This policy was implemented by setting a constraint on coal power generation to reach zero by 2035.	Same as in Current Policies scenario.
	Nuclear power relicensing	We assume no new nuclear generation is deployed, in line with Minnesota policy, but assume relicensing of existing facilities through 2050.	Same as in Current Policies scenario.
Federal – IRA	Section 13101: Production tax credit (PTC)	Modeled as a $26/MWh subsidy for solar, wind, geothermal, and biomass technologies through 2024. We assume that all projects pay prevailing wages. A 7.5% reduction in the credit value is assumed due to the transferability provision.	Same as in Current Policies scenario.
	Section 13102: Investment tax credit (ITC) extension	Modeled as a 30% subsidy for offshore wind and storage technologies through 2024, with the simplifying assumption that all projects pay prevailing wages. A 7.5% reduction in the credit value is assumed due to the transferability provision.	Same as in Current Policies scenario.
	Sections 13701 and 13702: New clean electricity PTC and ITC	Modeled in the same way as sections 13101 and 13102 through 2030, with phasedown after 2030.	Same as in Current Policies scenario.
	Section 13302: Residential clean energy credit	Modeled by updating the rooftop ITC, with phasedown after 2030.	Same as in Current Policies scenario.
	Section 13015: PTC for existing nuclear	Modeled as a $15/MWh subsidy for nuclear technologies through 2030, with the simplifying assumption that all projects pay prevailing wages. We assume that these incentives, in combination with non-federal incentives and zero-emission credits, prevent the economic retirement of nuclear plants. As such, we model Georgia Vogtle units 3&4 coming online by 2025 and maintain nuclear capacity at today's levels.	Same as in Current Policies scenario.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
	Section 50144: Energy community reinvestment financing	Modeled as $250 billion in loans and guarantees used to accelerate the retirement of coal-fired power generation and fund the construction of renewable electricity-generating capacity. Our central estimate is that this will accelerate the retirement of 38 GW of additional coal-fired capacity beyond already-scheduled retirements by 2030.	Coal is phased out by 2030 due to a combination of market forces, state coal-exit policies, and regulatory compliance costs. This was modeled by setting a national constraint on coal power to reach zero by 2030, and by prohibiting the buildout of new coal plants in all states.
	Section 13104 - 45Q: Extension of credits for captured CO_2	Extension of existing credits for captured CO_2 at $85/ton is implemented through 2030. We assume this subsidy will result in sequestration levels consistent with analyses by Rhodium Group[119] and Edmonds.[120] We modeled this exogenously by specifying sequestration for coal CCS and gas CCS, resulting in 130 MMTCO_2-eq annual sequestration nationally by 2030, which is held constant through 2050. In Maryland, gas CCS is introduced in 2035 at 0.6 MMTCO_2-eq annual sequestration, which is held constant through 2050. In Minnesota, CCS technologies are allowed to begin competing with other electricity generation technologies beginning in 2035.	Same as in Current Policies scenario.
Other states	Renewable energy targets	Current state-level RPS targets are modeled. City- and utility-level goals were assumed to be supportive of these state-level targets and additional only in cases where a higher percentage is targeted. These were implemented by setting a minimum % of total electricity load to be met by renewable generation.	Same as in Current Policies scenario.

[119] Larsen, J.; King, B.; Hiltbrand, G.; Herndon, W. *Capturing the Moment: Carbon Capture in the American Jobs Plan*. Rhodium Group. Available at: https://rhg.com/research/carbon-capture-american-jobs-plan/.

[120] Edmonds, J.; Nichols, C.; Adamantiades, M.; Bistline, J.; Huster, J.; Iyer, G.; Johnson, N.; Patel, P.; Showalter, S.; Victor, N.; Waldhoff, S.; Wise, M.; Wood, F. Could Congressionally Mandated Incentives Lead to Deployment of Large-Scale CO2 Capture, Facilities for Enhanced Oil Recovery CO2 Markets and Geologic CO2 Storage? *Energy Policy* **2020**, 146, 111775. Available at: https://doi.org/10.1016/j.enpol.2020.111775.

Supplementary Table B3. Representation of policies for the transportation sector in GCAM-USA-CGS.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Minnesota	Vehicle miles traveled (VMT) per capita reductions	Not modeled in this scenario.	This policy was modeled based on Minnesota Department of Transportation goals to reduce vehicle miles traveled (VMT) per capita through the next few decades.[121] The 2019 baseline of 10,691 VMT per capita serves as the point of reference against which VMT per capita decrease in future years is measured. Specifically, the following goals are used: -4% (2025), -8% (2030), -11% (2035), -14% (2040), and -20% (2050). The VMT reductions were modeled by decreasing passenger vehicle transportation through 2050, aiming to achieve the intended targets when aggregating all road transport, including freight. VMT reductions are modeled as reductions in passenger-miles traveled. These units represent the transportation of a single person over a single mile and are not equivalent to VMT. However, the percentage changes between model years can be interpreted in terms of the percentage change in VMT. Passenger-miles can be converted into VMT by using assumptions on the average number of people transported and the average miles traveled.
	Electric vehicle sales targets	Not modeled in this scenario.	The only scenario with EV sales targets is the PPP scenario before Federal rollbacks. EV sales targets modeled follow the trajectories of Advanced Clean Cars II and Advanced Clean Trucks, policies that exist in CA and other states. **Rollbacks:** The California waiver, which is the basis for states with the Advanced Clean Cars II and Advanced Clean Trucks policies, is assumed to be rescinded. As such, EV sales targets for Minnesota are removed in the rollback scenarios.
	Clean Transportation Standard	Not modeled in this scenario.	The Clean Transportation Standard was modeled as an increasing share of transportation liquid fuels provided by biofuels or qualifying low-carbon intensity fuels. With goals of 25% blend in 2030, 75% in 2040, and 100% in 2050, the pathways modeled approximately follow those goals. The total volume of biofuels or qualifying low-carbon intensity fuels depends on the amount of vehicle electrification.

[121] Minnesota Department of Transportation. *Statewide Multimodeal Transportation Plan*; 2022. https://minnesotago.org/final-plans/smtp-final-plan-2022.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Federal – IRA	Section 13401 - 30D: Clean vehicle credit	Same as in the Potential Policies Pathway scenario.	This tax credit has a maximum value of $7,500 with an EV being eligible for half of the credit if its battery meets domestic assembly requirements and other half of the credit is contingent upon a specific share of the minerals used in the battery being sourced for North American or other free trade countries. We assume that the US auto manufacturing sector will reorient itself so that all new EVs produced by 2030 will meet these requirements, and that by 2025, half of EVs sold will meet these requirements. If the car meets the battery assembly and mineral sourcing requirements, a consumer can receive the full value of the tax credit provided that their income does not exceed the income eligibility threshold, and that the sales price of the car does not exceed MSRP eligibility thresholds. We find that 89% of Americans meet the income requirement and further assume that they would only purchase EVs that meet the MSRP threshold. Altogether, this yields an EV tax credit with an effective value of $6,673, implemented as a capital cost reduction. We assume that for the 2031-2035 model period that the tax credit takes on a value 40% of the 2030 value because it is scheduled to expire in 2032. **Rollbacks:** Modeled as cost reduction only for 2025 modeling period.
	Section 13404: Alternative refueling property credit	Same as in the Potential Policies Pathway scenario.	This credit is assumed to be a $1,000 property credit available for LDV charging infrastructure for individuals in rural and low-income census tracts. Based on census data, 17.4% of Americans live in counties that are either rural or low-income, so the $1,000 property credit is modeled as a weighted average national subsidy of $174 for capital infrastructure cost for EVs. We assume that for the 2031-2035 model period that the tax credit takes on a value 40% of the 2030 value because it is scheduled to expire in 2032. **Rollbacks:** Modeled as cost reduction only for 2025 modeling period.
	Section 13403 - 45W: Commercial clean vehicle credit	Same as in the Potential Policies Pathway scenario.	This tax credit is modeled as a $40,000 capital cost reduction for electric heavy duty freight trucks, and a $7,500 capital cost reduction for electric medium duty and light duty freight trucks. We assume that for the 2031-2035 model period that the tax credit takes on a value 40% of the 2030 value because it is scheduled to expire in 2032. **Rollbacks:** Modeled as cost reduction only for 2025 modeling period.
	Sections 13201, 13202, and 13203: Extension of incentives for biofuels	Same as in the Potential Policies Pathway scenario.	Implemented as subsidies in 2025 for biodiesel, cellulosic ethanol, FT biofuels, cellulosic ethanol with CCS, and FT biofuels with CCS. We assume that jet fuel is the first market for FT biofuel, and FT biofuels therefore receive the aviation fuel credit. **Rollbacks:** No modeling change.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Federal – BIL	Section 11401 and 11403: Grants from charging and fueling infrastructure, Carbon Reduction Program, and National Electric Vehicle Formula Program	Same as in the Potential Policies Pathway scenario.	We assume BIL allocates \$10.7 billion investment to LDV EV charging infrastructure**.** This investment is implemented as an \$802 reduction in per vehicle charging infrastructure cost, based on modeled vehicle fleet size in GCAM-USA-CGS 6.0, for model periods 2025 and 2030. **Rollbacks:** Modeled cost reduction only for 2025 modeling period.
	Section 11115 and 11403: Congestion mitigation and air quality improvement program, and Carbon Reduction Program	Same as in the Potential Policies Pathway scenario.	We assume BIL allocates \$4.24 billion investment to medium- and heavy-duty truck EV charging infrastructure. This investment is implemented as a \$9,211 reduction in per vehicle charging infrastructure cost, based on fleet size in GCAM-USA-CGS 6.0, for model periods 2025 and 2030. **Rollbacks:** Modeled cost reduction only for 2025 modeling period.
	Sections 71101 and 30018: Clean school bus program and Grants for buses and bus facilities	Same as in the Potential Policies Pathway scenario.	BIL's \$5 billion investment in school bus electrification is implemented as a \$25,000 reduction in per vehicle purchase cost for model periods 2025 and 2030. A \$2.6 billion investment in transit bus electrification is implemented as a \$29,167 reduction in per vehicle purchase cost for model periods 2025 and 2030. **Rollbacks:** Modeled cost reduction only for 2025 modeling period.
Federal – regulations	CAFE standards for LDVs	Same as in the Potential Policies Pathway scenario.	Internal combustion engine GHG performance standards are modeled to reflect efficiency improvement rates from recently updated Corporate Average Fuel Economy standards so that nationally, fuel efficiency reaches 166 gCO_2/mi for new passenger cars and 219 gCO_2/mi for new SUVs by 2030. Note: these are based on the NHTSA minimum standard and are not inclusive of ZEVs. **Rollbacks:** Modeled standards only for 2025 modeling period. With the CAFE penalty set to \$0 in 2025 HR1, we assume no regulatory impact of CAFE standards beyond 2025.
Other	Electrification of military and off-highway vehicles	Not modeled in this scenario.	Military and off-highway emissions were assumed to reduce to 80% of 2020 levels by 2050, declining linearly from 2025.

Supplementary Table B4. Representation of policies for the buildings sector in GCAM-USA-CGS.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Minnesota	Natural Gas Efficiency Resource Standard	Not modeled in this scenario.	A natural gas efficiency target of a 2% annual reduction in natural gas consumption in aggregate commercial and residential buildings is modeled from 2030 to 2050.
	Building Code Efficiency Standards	Energy efficiency goals outlined in the existing building energy codes, detailed in Minn. Stat 326B.10, are modeled.	Enhanced building codes include increasing energy efficiency for residential and commercial buildings. These building goals can leverage energy savings from integration and buildout of rooftop and distributed solar power, which is explicitly modeled as supportive of this policy. Policy goals for new buildings of an 80% reduction in net annual energy consumption by 2036 (relative to 2004 standards) for commercial buildings and a 70% reduction by 2038 for residential buildings (relative to 2006 standards) are modeled.
	Building retrofitting (commercial)	Not modeled in this scenario.	Retrofitting commercial buildings to achieve a 40% reduction in net annual energy consumption compared to 2004 building code standards for large commercial buildings (greater than 50,000 sq ft) is modeled. This policy was modeled as decreasing energy use intensity, considering the build-out of rooftop solar, such that the aggregate energy use intensity of commercial buildings in 2050 would be at least 40% lower than in 2005. This is equivalent to achieving 50% of new construction efficiency standards.
	Residential Weatherization	Existing residential building retrofitting is modeled through increases in building shell efficiency above the baseline trajectory, representing building code goals through the mid-2030s.	Similar to the Current Policies scenario, with additional weatherization that further supports the goals outlined in enhanced building codes above.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Federal – IRA	Section 13303: Energy-efficient commercial building deduction	Same as in the Potential Policies Pathway scenario.	This provision is estimated to reduce commercial HVAC costs by 3%. We modeled this provision as a 3% subsidy for commercial high-efficiency heating and cooling technologies in 2025 and 2030. **Rollbacks:** Modeled as a subsidy only in the 2025 modeling period.
	Sections 13301 - 25C and 13304 and 50121: Energy efficient home improvement credit, Energy efficient home credit, and home energy efficiency credit	Same as in the Potential Policies Pathway scenario.	These provisions include subsidies for replacing existing end-use equipment with more efficient alternatives, such as heat pumps, offsetting a share of labor and installation costs for technologies that generate renewable energy, and building new homes that save 50% more on heating and cooling energy compared to 2006. These provisions are modeled by improving shell efficiency in residential buildings based on the AEO 2022 “Alternative Policies – Extended Credit” case.[122]
	Section 51022: High efficiency home rebate program	Same as in the Potential Policies Pathway scenario.	Modeled as a subsidy to high-efficiency technologies in residential buildings in 2025 and 2030. We model the following consumer credits as available to the lower 6 income deciles: $1,750 to electric heat pump water heaters, $4,000 for electric heat pumps for space heating, $420 for electric ovens, $420 for electric heat pump clothes dryers, $1,600 for high-efficiency air conditioning. Adequate funding is assumed for this program. **Rollbacks:** Modeled as a subsidy only in the 2025 modeling period.

[122] U.S. Energy Information Administration. *Annual Energy Outlook 2022*. EIA. https://www.eia.gov/outlooks/archive/aeo22/ (accessed 2023-06-23).

Supplementary Table B5. Representation of policies for the industrial sector in GCAM-USA-CGS.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Minnesota	Natural Gas Efficiency Target	Not modeled in this scenario.	A natural gas efficiency target of 3% annual reduction in natural gas consumption in aggregate industry is modeled beginning in 2030 through 2050.
Federal – IRA	Section 13104 - 45Q: Extension of credits for captured CO_2	Same as in the Potential Policies Pathway scenario.	Extension of existing credits for captured CO_2 at $85/ton is implemented through 2030. We assume this subsidy will result in sequestration levels consistent with Rhodium Group analysis.[123] We modeled this exogenously by specifying sequestration across various industrial sectors, resulting in 93 $MMTCO_2$-eq annual sequestration nationally in 2030, and held constant through 2050.
	Sections 13204: Production credit for clean hydrogen	Same as in the Potential Policies Pathway scenario.	Modeled as different subsidies to hydrogen technologies depending on their carbon intensities. We assume that fossil hydrogen without CCS doesn't qualify and fossil hydrogen with CCS claims 45Q instead, and that 50% of projects pay prevailing wages.
	Section 13501 - 48C: Manufacturing investment tax credit for advanced energy projects	Same as in the Potential Policies Pathway scenario.	Designates $10 billion for industrial and manufacturing facilities aiming to equip themselves with technology to curtail GHG emissions.[124] This was modeled by specifying electrification rates aligned with an Energy Innovation analysis on low-temperature heating in the industrial sector.[125]

[123] Larsen, J.; King, B.; Hiltbrand, G.; Herndon, W. *Capturing the Moment: Carbon Capture in the American Jobs Plan*. Rhodium Group. Available at: https://rhg.com/research/carbon-capture-american-jobs-plan/.

[124] *Inflation Reduction Act of 2022*. *H.R.5376*.

[125] Rissman, J. *Decarbonizing Low-Temperature Industrial Heat in the U.S.* https://energyinnovation.org/wp-content/uploads/2022/10/Decarbonizing-Low-Temperature-Industrial-Heat-In-The-U.S.-Report-1.pdf (2022).

Supplementary Table B6. Representation of policies for the waste sector.

Level of government	Modeled policy	Current Policies scenario (includes BIL & IRA)	Potential Policies Pathway scenario
Minnesota	Waste sector emissions	Landfill emissions were modeled endogenously to grow with state GDP. All other emissions and sinks in the waste sector were assumed to remain constant at 2020 levels. This sector has very low emissions (1.27 $MMTCO_2$-eq in 2020), so the impact of this assumption is minimal.	Landfill emissions were assumed to decrease by about 50% through 2050 relative to 2020 levels. This assumption assumes technology deployment and strategies that reduce landfill methane emissions, and follows goals established by Maryland's landfill gas reduction policy as an example of a leading state policy in this sector. Additionally, Minnesota municipal landfill data was used with the EPA LandGEM tool to calculate landfill methane generation and methane collection efficiencies, averaged across 2010-2023. The average collection efficiency was found to be 48% for those landfills with GCCS.

Note: Agricultural emissions and emissions from land use, land-use change, and forestry (LULUCF) were modeled separately outside of GCAM-USA-CGS. Modeling inputs and assumptions for these sectors is covered in the Agriculture and LULUCF modeling scenario descriptions section.

Appendix C: Consumption-based emissions

The Minnesota Climate Action Framework modeling and data offer insight into the greenhouse gases released directly from within our state's borders. These emissions include sources such as vehicle tailpipes, fossil fuel power plants, livestock, landfills, factories, and home furnaces. While these sources account for a significant portion of the greenhouse gas emissions Minnesotans are responsible for, we can also take additional climate action by addressing "consumption-based" emissions: in other words, the GHGs emitted by the production and disposal of goods we purchase and consume.

Greenhouse gases are released throughout the entire life cycle of products and materials, from mining and manufacturing to transportation and disposal. These emissions are all important to consider regardless of whether they occur in Minnesota, in another state, or in a country on the other side of the world. In this way, Minnesotans are responsible for the GHGs from materials we purchase and consume regardless of where on the planet the emissions occurred.

While Minnesota's Greenhouse Gas Inventory does not include *data* on these out-of-state, consumption-based emissions, many of the recommended Climate Action Framework *action steps* can reduce both types of emissions. Importantly, many of these consumption-focused options are highly local, approachable actions that individual Minnesotans can take to help counteract climate change. Such actions can be particularly impactful because when consumption-based emissions are factored in, the total emissions attributed to Minnesota are actually estimated to be around 40%* higher than the levels reflected by the "in-state" data alone.

* Consumption-Based Greenhouse Gas Emissions Results for the State of MN for 2012-2019

Appendix D: REMI PI+ sectors

Supplementary Table D1. Industries for REMI PI+

Index	Industry	NAICS Code
1	Forestry, fishing, and hunting	**113-115**
1	Forestry and Logging; Fishing, hunting and trapping	113-114
2	Support activities for agriculture and forestry	115
2	Mining	**21**
3	Oil and gas extraction	211
4	Mining (except oil and gas)	212
5	Support activities for mining	213
3	Utilities	**22**
6	Utilities	22
4	Construction	**23**
7	Construction	23
5	Manufacturing	**31-33**
8	Wood product manufacturing	321
9	Nonmetallic mineral product manufacturing	327
10	Primary metal manufacturing	331
11	Fabricated metal product manufacturing	332
12	Machinery manufacturing	333
13	Computer and electronic product manufacturing	334
14	Electrical equipment, appliance, and component manufacturing	335
15	Motor vehicles, bodies and trailers, and parts manufacturing	3361-3363
16	Other transportation equipment manufacturing	3364-3369
17	Furniture and related product manufacturing	337
18	Miscellaneous manufacturing	339
19	Food manufacturing	311
20	Beverage and tobacco manufacturing	312
21	Textile mills and textile product mills	313, 314
22	Apparel, leather and allied product manufacturing	315, 316
23	Paper manufacturing	322
24	Printing and related support activities	323
25	Petroleum and coal products manufacturing	324
26	Chemical manufacturing	325
27	Plastics and rubber products manufacturing	326
6	Wholesale trade	**42**
28	Wholesale trade	42
7	Retail trade	**44-45**
29	Retail trade	44-45

Index	Industry	NAICS Code
8	Transportation and warehousing	**48,492-493**
30	Air transportation	481
31	Rail transportation	482
32	Water transportation	483
33	Truck transportation	484
34	Couriers and messengers	492
35	Transit and ground passenger transportation	485
36	Pipeline transportation	486
37	Scenic and sightseeing transportation and support activities for transportation	487, 488
38	Warehousing and storage	493
9	Information	**51**
39	Publishing industries, except Internet	513
40	Motion picture and sound recording industries	512
41	Data processing, hosting, and related services; Other information services	518, 519
42	Radio and television broadcasting, media streaming distribution services, social networks, and other media networks and content providers	5161, 5162
43	Telecommunications	517
10	Finance and insurance	**52**
44	Monetary authorities - central bank, credit intermediation, and related activities	521, 522
45	Securities, commodity contracts, investments, and funds and trusts	523, 525
46	Insurance carriers and related activities	524
11	Real estate and rental and leasing	**53**
47	Real estate	531
48	Rental and leasing services; Lessors of nonfinancial intangible assets	532, 533
12	Professional, scientific, and technical services	**54**
49	Professional, scientific, and technical services	54
13	Management of companies and enterprises	**55**
50	Management of companies and enterprises	55
14	Administrative, support, waste management, and remediation services	**56**
51	Administrative and support services	561
52	Waste management and remediation services	562
15	Educational services; private	**61**
53	Educational services; private	61
16	Health care and social assistance	**62**
54	Ambulatory health care services	621
55	Hospitals	622
56	Nursing and residential care facilities	623
57	Social assistance	624
17	Arts, entertainment, and recreation	**71**
58	Performing arts, spectator sports, and related industries	711

Index	Industry	NAICS Code
59	Museums, historical sites, and similar institutions	712
60	Amusement, gambling, and recreation industries	713
18	Accommodation and food services	**72**
61	Accommodation	721
62	Food services and drinking places	722
19	Other services (except public administration)	**81**
63	Repair and maintenance	811
64	Personal and laundry services	812
65	Religious, grantmaking, civic, professional, and similar organizations	813
66	Private households	814
20	State and Local Government	**NA**
67	State and Local Government	NA
21	Federal Civilian	**NA**
68	Federal Civilian	NA
22	Federal Military	**NA**
69	Federal Military	NA
23	Farm	**111, 112**
70	Farm	111, 112

Appendix E: GCAM capital and energy expenditure assignments to REMI industries

Supplementary Table E1. Shares for assigning costs in REMI.

GCAM category	REMI industry	Share*
comm	Educational services; private	0.4
	Hospitals	0.15
	Nursing and residential care facilities	0.15
	Professional, scientific, and technical services	0.08
	Warehousing and storage	0.03
	Retail trade	0.03
	Wholesale trade	0.03
	Performing arts, spectator sports, and related industries	0.015
	Museums, historical sites, and similar institutions	0.015
	Amusement, gambling, and recreation industries	0.015
	Accommodation	0.02
	Food services and drinking places	0.02
	Repair and maintenance	0.015
	Personal and laundry services	0.015
	Religious, grantmaking, civic, professional, and similar organizations	0.015
trn_aviation_intl	Air transportation	1
trn_freight	Rail transportation	1
trn_freight_road	Truck transportation	1
trn_pass	Transit and ground passenger transportation	1
trn_pass_road	Transit and ground passenger transportation	1
trn_shipping_intl	Water transportation	1
cement	Nonmetallic mineral product manufacturing	1
process heat cement	Nonmetallic mineral product manufacturing	1
other industrial energy use	Mining (except oil and gas)	0.11
	Wood product manufacturing	0.001
	Primary metal manufacturing	0.01
	Fabricated metal product manufacturing	0.005
	Machinery manufacturing	0.003
	Computer and electronic product manufacturing	0.01
	Electrical equipment, appliance, and component manufacturing	0.001
	Motor vehicles, bodies and trailers, and parts manufacturing	0.001
	Other transportation equipment manufacturing	0.001
	Furniture and related product manufacturing	0.001
	Miscellaneous manufacturing	0.002
	Food manufacturing	0.12

GCAM category	REMI industry	Share*
	Beverage and tobacco manufacturing	0.001
	Textile mills and textile product mills	0.001
	Apparel, leather and allied product manufacturing	0.001
	Paper manufacturing	0.026
	Printing and related support activities	0.002
	Petroleum and coal products manufacturing	0.22
	Chemical manufacturing	0.44
	Plastics and rubber products manufacturing	0.014
	Pipeline transportation	0.03
other industrial feedstocks	Mining (except oil and gas)	0.11
	Wood product manufacturing	0.001
	Primary metal manufacturing	0.01
	Fabricated metal product manufacturing	0.005
	Machinery manufacturing	0.003
	Computer and electronic product manufacturing	0.01
	Electrical equipment, appliance, and component manufacturing	0.001
	Motor vehicles, bodies and trailers, and parts manufacturing	0.001
	Other transportation equipment manufacturing	0.001
	Furniture and related product manufacturing	0.001
	Miscellaneous manufacturing	0.002
	Food manufacturing	0.12
	Beverage and tobacco manufacturing	0.001
	Textile mills and textile product mills	0.001
	Apparel, leather and allied product manufacturing	0.001
	Paper manufacturing	0.026
	Printing and related support activities	0.002
	Petroleum and coal products manufacturing	0.22
	Chemical manufacturing	0.44
	Plastics and rubber products manufacturing	0.014
	Pipeline transportation	0.03

*Commercial and Other industrial shares based on 2023 AQR data, Workbook: Air emissions - point source facility data