

Externality Tax Rates and Cost-Effective Mitigation with Coupled Pollutants: Carbon and Methane

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Abstract

Canonical theory holds that the efficient correction for pollution causing a diffuse negative externality is to tax the pollutant at its marginal social cost. This paper considers two co-produced pollutants that jointly give rise to a single externality. In a second-best setting where both pollutants are not optimally regulated, a tax on one should account for the combined externality from both. I look at the market failure of climate change and show that an extended general equilibrium Pigouvian rate for either a carbon or methane tax differs from its individual social cost due to the overlap in economic activities that generate these two major greenhouse gases. I also analyze the cost-effectiveness of carbon and methane taxes. In the U.S., nearly all anthropogenic carbon emissions are produced from fossil fuel combustion for energy, and almost half of methane emissions come from the fossil fuel energy system. I use a computable general equilibrium model of the United States to assess how economic interdependencies affect emissions in response to a set of policies. I find that the extended Pigouvian rate of a methane tax is over 200% above the social cost of methane, and the extended Pigouvian carbon tax is around 5% above the social cost of carbon. I determine that a combination of taxes at different rates, expressed in CO₂ equivalent terms, is most welfare-efficient. I test a sector-specific methane policy, and a set of alternative specifications including the near-term global warming potential of methane. I find that efficient policy shifts toward methane as methane emissions become more significant in alternative specifications.

1. Introduction

Methane (CH₄) is the second-largest anthropogenic greenhouse gas (GHG) of both global and U.S. emissions. A significant portion of methane emissions are produced as a byproduct of the fossil fuel energy system. The fossil fuel energy system is the predominant source of anthropogenic carbon dioxide (CO₂) emissions. This means that policies targeting either CO₂ or CH₄ also affect the other major GHG through economic-emissions interactions. Sectors outside of the fossil fuel energy system that emit methane will also be impacted by CO₂ policies

¹ Acknowledgements: I particularly thank Larry Goulder for guidance and Mitch Phillipson for technical help. I also thank Chenfei Qu, David Anthoff, Christopher Costello, Don Fullerton, Tom Rutherford, Teevrat Garg, Nicole Karwowski, the participants at AERE 2024 and 2025, EEE 2024, MEEW 2025, everyone at CoPS, and the Sustainable Solutions lab for helpful comments and suggestions. Financial support from the Precourt Energy Institute at Stanford University is gratefully acknowledged. All errors are my own.

via economic interdependencies. This makes it a complex problem to predict the overall emissions impact of a policy targeting either GHG, more so for policies on both GHGs in combination.

The outcome of any GHG policy will be the result of multiple effects happening simultaneously. As a GHG policy increases the cost of emitting activities, firms and consumers will substitute away from goods that are intensive in that GHG. They may switch to goods which are intensive in another GHG thereby increasing those emissions, or to goods that are less intensive in both GHGs thereby decreasing both emissions. High-emitting firms will tend to reduce production. Emissions of other GHGs generated by those firms will also decrease. Some firms with low emissions of the targeted GHG will increase production as their products become relatively cheaper. If those firms produce other GHGs, those emissions will increase. The option to directly reduce emissions intensity further complicates the effects. In a general equilibrium setting, each of these phenomena will have direct and indirect impacts, as prices, production, emissions, and emissions-intensities change and affect decisions throughout the interconnections in the economy.

These factors prompt my investigation of the interactions of emission reduction policies for both gases in a general equilibrium setting, to advance understandings of their relative and combined potential for mitigating climate change. This paper offers an integrated analysis, assessing the implications of connections between CO₂ and CH₄ for climate policy. It employs a general equilibrium model, representing carbon emissions and carbon reduction policy alongside methane emissions and methane reduction policy.

In this way, I am able to uncover key elements of the interactions between policies targeting these important GHGs. I determine optimal second-best externality-correcting prices for each type of emissions, accounting for the joint production of both GHGs. I characterize the joint response function when policies on both GHGs are applied separately and simultaneously, and identify welfare-efficient combined policies.

This paper is situated within the literature on optimal and second-best climate and pollution policy, along with studies estimating the emissions impacts of climate policies.

Research has looked in some detail at policies designed to reduce carbon emissions, with a notable subset including (Goulder 1995; Böhringer and Rutherford 1997; Babiker et al. 2003; Böhringer and Rutherford 2008; Metcalf and Weisbach 2009; Rausch et al. 2010; Siriwardana et al. 2011; Böhringer et al. 2012; Meng et al. 2013; Guo et al. 2014; Goulder and Hafstead 2018; Zhu et al. 2018; Metcalf and Stock 2020; Withey et al. 2022; Yan et al. 2023; Van Der Ploeg et al. 2024; Fried et al. 2024).

A less extensive literature has focused on methane reductions, including (Long et al. 2024; Cline 2020; Minihan and Wu 2014; Wheatley 2023).

The literature examining combinations of greenhouse gas policies is also limited and primarily focuses on the relative cost-effectiveness of including multiple greenhouse gas policies compared to CO₂-only regulations. (Böhringer et al. 2004) use a multi-region dynamic CGE-based integrated assessment model, with a representative agent maximizing welfare across time, and find lower

adjustment costs with the ability to flexibly reduce either CO₂ or CH₄. (Aaheim et al. 2006) build a highly stylized, two-sector, global numerical model with emissions that links emissions to energy and under a 100-year radiative forcing constraint, finding some cost savings from including non-CO₂ reduction policies relative to CO₂-only. (Weyant et al. 2006) compare results from a set of integrated assessment models and find substantial variability in compliance cost estimates but general agreement on lower costs associated with multi-gas reduction scenarios. (Morris et al. 2012) examine the construction and robustness of marginal cost curves, find that incorporating other GHGs lowers the slope. (Liu and Wu 2017) use a ten-sector Social Accounting Matrix model² for China, and show that taxing multiple greenhouse gases causes different emission reductions across gases and across sectors, along with lower price impacts from non-CO₂ taxes. (Zhang and Xu 2018) develop a dynamic programming model that incorporates emissions and regulation for both CO₂ and CH₄, providing comparative solutions that indicate that taxes on both GHGs are preferable to quotas or any mix of a quota and tax. (Nong et al. 2021) employ a version of the static, multi-region GTAP CGE model to quantify the additional economic costs in each region associated with taxing non-CO₂ emissions compared to a CO₂ tax alone.

I contribute to this literature by focusing on the combination of carbon and methane policies, considering closely how these policies affect emissions of both GHGs, and how the policies interact. This paper uses a static computable general equilibrium (CGE) model of the United States to capture the key economic and emissions interdependencies and highlight the insights with minimal assumptions and more transparent methodology. My model incorporates emissions of each GHG directly linked to the emitting sectors, and uses taxes to represent a range of relevant emission reduction policies³.

I highlight two main findings. First, a tax on either greenhouse gas equal to its social cost⁴ is insufficient to fully internalize the climate externality when gases are jointly produced. In a second-best setting with a Pigouvian tax⁵ on only one of the two major greenhouse gases, Pigouvian theory implies that the appropriate tax rate must account for the net marginal climate damages arising from the economically linked greenhouse gases. I find that the emissions of the two major GHGs are complements in aggregate: tightening or loosening policy on one gas induces positively correlated changes in the other through economy-wide general equilibrium and emissions responses. I therefore determine extended general equilibrium externality tax rates that scale the tax on each individual GHG to account for the climate damages from the associated emissions of the

² A Social Accounting Matrix model (SAM) extends from Input-Output matrices to include a representation of secondary income distribution.

³ I use taxes as a simplified representation of greenhouse gas reduction policies on emissions. Other policy designs are possible, with differences in the breadth of sources covered, and in the instruments used to reduce emissions. The key insights offered here would likely apply in other cases, though a full assessment of other policy designs is beyond the scope of this paper.

⁴ The social cost of a greenhouse gas measures the cost of global damages caused by an incremental change in emissions of that greenhouse gas, all else equal.

⁵ Following foundational economic theory (Pigou 1920), setting a tax on a negative externality-causing activity will price in the externality, thereby adjusting costs throughout the economy and changing behaviour accordingly, internalising that cost and reducing the quantity of the externality to the socially optimal level. For each greenhouse gas, standard theory says that the first-best tax level on a GHG should equal its social cost, often called a Pigouvian tax.

complementary gas. I find that a CH₄ tax over 200% higher than its standard Pigouvian rate internalizes the combined climate externality. I find that a CO₂ tax 5% higher than its standard Pigouvian rate internalizes the combined climate externality.

Second, I examine the cost-effectiveness of separate and combined GHG taxes and find that a CH₄ tax is much less costly to welfare⁶ per ton of emissions mitigated than a CO₂ tax. However, combined policies of different stringencies on both CO₂ and CH₄ are generally the most welfare-efficient for a given reduction target. I determine the least-cost policy combination that would achieve a Paris Agreement-aligned emission reduction target.

I explore alternate assumptions and policy scenarios: using a higher relative warming potential for methane; a higher estimate of U.S. oil and gas methane emissions; and a methane policy limited to the oil and gas sector. I determine the least-cost combined CO₂ and CH₄ policies for all scenarios. I find that the least-cost combination policy shifts toward the methane tax as methane emissions become more significant.

I further examine and illustrate the interaction effects between policies on the two major GHGs by imposing taxes on CO₂ and CH₄ emissions at different levels individually and in combination.

Overall, my findings quantify the significance of these economic-emissions interactions for policies on multiple greenhouse gases. I demonstrate that it is essential to account for these effects in policy discussion and analysis, and provide a framework to guide ongoing policy design, targets, and implementation.

In the rest of this section, I provide additional background on U.S. emissions with a focus on methane. In section 2, I present my model in detail. Section 3 outlines the policy scenarios I consider in this analysis. In section 4, I discuss my results in detail. The final section concludes.

1.1 Emissions Background

The United Nations Framework Convention on Climate Change has set a ceiling of 1.5°C above pre-industrial global average temperature (or as close as possible) to mitigate the worst damages, yet global emissions continue to rise, even as we approach that threshold.

⁶ Welfare in the model is measured in terms of equivalent variation for the single representative domestic consumer, with all tax revenues rebated lump-sum.

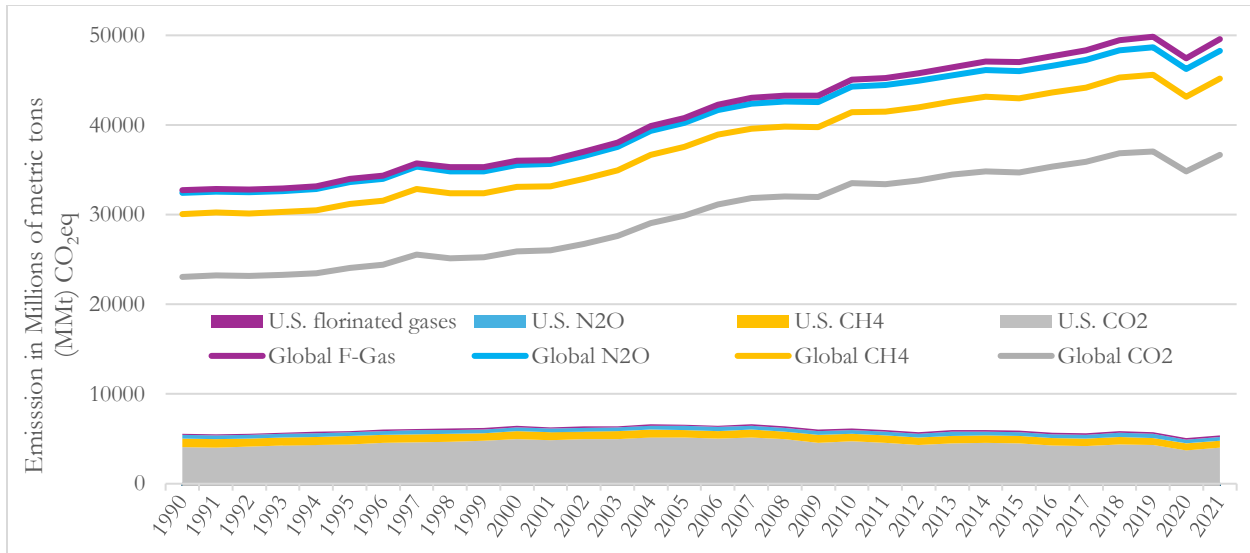


Figure 1: Global GHG emissions (stacked lines) with U.S. emissions overlaid (stacked area), highlighting the U.S. share of global emissions over time⁷.

Figure 1 above shows U.S. emissions dropping from 17% of global emissions in 1990 to 11% in 2021, as global emissions increased and U.S. emissions gradually decreased since 2007. U.S. emissions remain disproportionately significant, as U.S. population went from 5% to 4% of global population⁸ over the same period.

Carbon dioxide made up the majority of greenhouse gas emissions (80%) from the United States in 2022, while methane emissions were also considerable (11%). Table 1 below shows data from the most recent greenhouse gas inventory (EPA 2024).

⁷ Global emissions data was taken from https://www.climatewatchdata.org/ghg-emissions?breakBy=gas&chartType=area&end_year=2021&source=Climate%20Watch&start_year=1990. U.S. emissions are from the U.S. EPA

<https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/gas/all>

⁸ Population data taken from the United Nations Population Division at <https://population.un.org/dataportal/data/indicators/70/locations/900,840/start/1990/end/2021/table/pivotbylocation?df=c2a33780-7bf5-4dc7-99fe-dfc398f7f074>

Table 1: Greenhouse Gas Emissions for the United States, 2022. All values are in MMt CO₂eq

GHGs emissions gross	6,343		
GHGs net (sources and sinks)	5,489		
	% of CO ₂		% of gross GHGs
CO₂	4,689	100%	80%
Fossil Fuel Combustion	4,342	93%	74%
Transportation	1,751	37%	29%
Electric Power Sector	1,532	33%	26%
Industrial	801	17%	13%
Residential	334	7%	6%
Commercial	259	6%	4%
U.S. Territories	23	0%	0%
Other CO₂	354	8%	6%
	% of CH ₄		% of gross GHGs
CH₄	702	100%	11%
Fossil Fuel activities	282	40%	4%
Agriculture	279	40%	4%
Waste	141	20%	2%

93% of the U.S. CO₂ emissions were a direct product of fossil fuel combustion for energy. The historically central economic role of fossil fuel energy means that extensive structural changes are required to reduce those emissions. 40% of U.S. methane emissions in 2022 were related to fossil fuel activities. Methane emissions are a byproduct of economic activities, not a direct outcome: we can limit methane emissions with changes in technology and practices while maintaining the economic benefits of those activities, as detailed immediately below. Some methane emissions - such as those from enteric fermentation - do not have current zero-emission technologies at any cost.

1.2 Methane Sources and Abatement Options

1.2.a Fossil Fuel Activities

Energy-related emissions of methane are primarily from the extraction, distribution, and processing of oil and gas, and from underground coal mining. Emissions are generated from oil production when commercial gas recovery isn't undertaken, or from leaks throughout the system of commercial gas production, from extraction through to final combustion. Natural gas is predominantly methane, and often a co-product with oil extraction. Underground coal mines release methane incidentally, as well as intentionally for safety reasons. Abatement options for oil and gas extraction, and for coal mining focus on equipment and practices to recover the methane for various uses, or flaring⁹. For gas production, processing, and distribution, abatement options include better capture, leak

⁹ Flaring burns the methane, transforming the vast majority into carbon dioxide, commonly assumed at around 98% efficiency. Recent research finds a much lower efficiency, including unlit flares, and therefore much higher percentage of uncombusted methane entering the atmosphere than currently estimated (Plant et al. 2022)

detection and maintenance, equipment replacement to reduce leaks, and to some extent improvements in the efficiency of use.

1.2.b Agriculture

Agricultural emissions of methane are primarily related to livestock, both enteric fermentation and manure, as well as rice cultivation. Enteric fermentation is the natural digestive process of livestock and abatement options focus on increasing the growth and production efficiency of livestock products, reducing the emissions per unit, such as administering vaccines, growth hormones and antibiotics, as well as feed additives or intensive grazing. While there is a cost for intermediate goods related to these abatement actions, it seems reasonable to assume that they are less significant than the change in agricultural practices (e.g. vaccine cost vs cost of administering the vaccine), and I represent abatement costs as additional labour and capital, in line with abatement costs for all other sectors in the model. Livestock manure generates methane, and the abatement options involve equipment and practices to concentrate, collect, and capture the emissions for use or flaring. Rice farming generates emissions from anaerobic decomposition in flooded fields, and abatement options involve various water management, tillage, and fertilizer application practices.

1.2.c Waste

Waste emissions of methane are from anaerobic decomposition in landfill and water treatment. Abatement options for landfills involve collecting the methane for use or flaring, as well as some diversion of organic waste. Emissions in water treatment are from organic decomposition and abatement options involve equipment and infrastructure upgrades.

1.3 Emissions in the Model

To model the CH₄ emissions and options for abatement as described immediately above, I associate emissions directly with the productive activities of each relevant economic sector in a way that allows firms to reduce the methane intensity of their activities. I link CH₄ emissions to the labour and capital inputs of production for each firm. Firms can then choose to pay for emissions-reducing equipment, or emission-reducing additional labour (representing activities such as leak inspections, or alternative agricultural practises). This structure allows for a concise and consistent representation, while capturing the important mechanisms involved.

To model the costs of reducing methane emissions within each sector, I use marginal abatement costs estimates from the U.S. Environmental Protection Agency (EPA 2019). The EPA calculates abatement potential by GHG type per economic sector by country, consistent with national GHG Inventory emissions data (EPA 2024). The underlying data used for the United States is particularly detailed. The bottom-up, engineering-based, peer-reviewed methods provide sector-specific abatement costs from feasible and financially viable technologies, proportionate to the sector-specific emissions (Ragnauth et al. 2015; Gallaher et al. 2005). The complementarity structure of my CGE model allows me to incorporate these cost estimates directly, such that firms will only undertake a particular level of abatement when it is least costly relative to other choices.

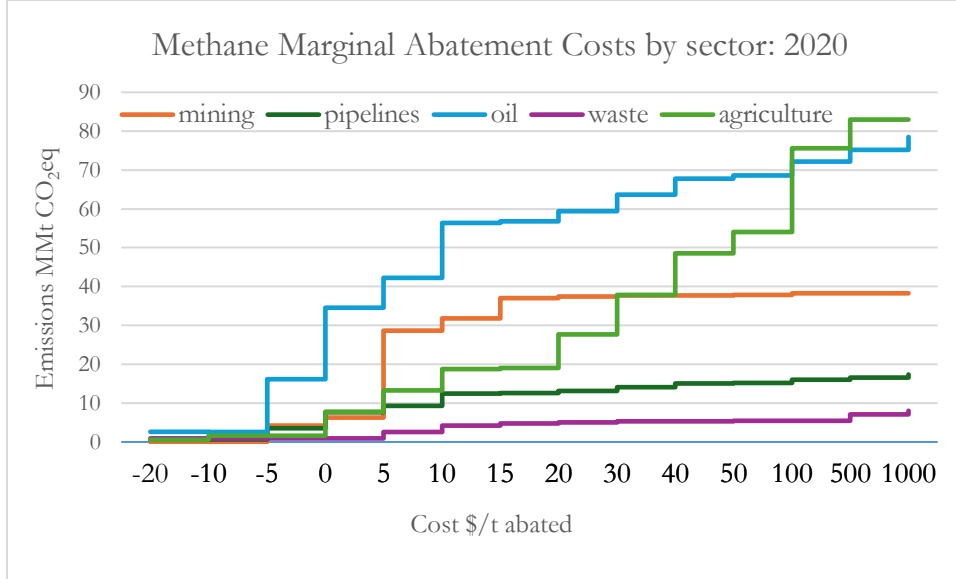


Figure 2: Abatement Cost 'curves' for each sector estimated for 2020¹⁰

Figure 2 above shows the abatement cost estimates from the EPA Global Non-CO₂ Greenhouse Gas Emission Projections & Mitigation Report¹¹. As described in more detail in Section 2 below, I represent abatement as a step function, without interpolation. Two additional assumptions were made to fit the abatement estimates to the economic data: I subsume negative abatement costs cumulatively into the lowest positive costs; and I align the emitting sectors with those in the economic data.

To model CO₂ emissions, I adopt the common approach of focusing in detail on the representation of energy production, and associate CO₂ emissions with that energy production. I distinguish between direct fossil fuel energy and electricity, between different fossil fuels, and between the most relevant inputs to electricity (coal, gas, and non-emitting generation). This structure allows for firms and consumers to respond to the price effect of carbon emission reduction policies, accounting for both direct and indirect costs of energy-related emissions throughout domestic production and consumption.

2. The model

The general equilibrium model contains a set of 76 representative firms that produce goods and services for domestic use and export. The model includes a range of taxes, including the taxes on greenhouse gases. The provision of public services is represented as 5 of the 76 sectors (defense, federal non-defense, state govt, fed and state/local enterprises). Fossil fuel and electricity energy provision is separated from other sectors in the production structure to enable a specific treatment

¹⁰ The EPA model reports abatement costs in 5-year increments. To estimate abatement potential in 2022 I interpolate linearly between the costs for 2020 and 2025.

¹¹ The baseline emissions per sector used in this paper come from the same report. The descriptions of CH₄ emissions and abatement options for each sector in section 1.2 Methane Sources and Abatement Options above are summarized from the same report.

for the relationship between energy demand, CO₂ emissions, and the impact of a CO₂ tax. Methane emissions and a methane tax are linked to production activities of the relevant sectors. A single representative household consumes final demand goods and services gross of taxes. Tax revenue in the model is passed directly to the representative household in a lump-sum manner.

The model is adapted from the WiNDC canonical U.S. national model. Adaptations include sector disaggregation, re-structuring of intermediate production to incorporate the detail on energy production and CO₂ emissions, and linking methane emissions and emission intensities with value-added factors as described below.

2.1 Firm Behaviour

Producers maximize profits, selecting quantities of outputs and inputs at given prices including the existing output tax, and taking account of the emissions implications and tax obligations consequent to a CO₂ tax on fossil fuel energy inputs, and a CH₄ tax linked to methane-causing value-added activities. Profit for the representative firm/sector j , with inputs from all other non-energy firms indexed by i , is determined by:

$$\pi_j = (1 - \tau_{Y_j}) p_{Y_j} Y_j - p a_i M_{i,j} - c(E_j) - c(VA_j) \quad \forall i \quad (1)$$

The first term on the right-hand side is revenue, the quantity of the good Y_j produced at price P_{Y_j} , minus exogenously set ad valorem taxes paid. The second term is the costs of intermediate materials and services inputs supplied by all non-energy sector firms i at price $p a_i$. The third term is the cost function of the energy input which includes the energy sectors goods, and a tax on carbon for the fossil fuels in energy. The last term is the cost function of the value-added input for each firm j which includes a tax on methane emissions associated with the firm activities.

Firms produce a single representative good from a set of inputs combined in a nested structure to allow for specific representations of substitutability of the inputs at each level. At the top level, a composite of intermediate goods from all other non-energy firms is combined with the value-added and energy composite with a Constant Elasticity of Substitution (CES) function.

$$Y_j = \left(a_{TY,j} M_j^{\frac{\sigma-1}{\sigma}} + (1 - a_{TY,j}) VAE_j^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (2)$$

Where Y_j is output from firm j , M_j is the composite intermediate materials and services input, VAE_j is the composite of value-added factors and energy, E_j , each of which are composed from production nests at the levels below.

M_j aggregates the combined material and services inputs from all non-energy sectors with a CES function.

$$M_j = \left(\sum a_{i,j} x_{i,j}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \quad \sum a_{i,j} = 1 \quad \forall \text{ sectors } i \quad (3)$$

VAE_j aggregates the combined value-added factors with E_j , total energy inputs for sector j that includes direct fossil fuel energy and electricity.

$$VAE_j = \left(a_{VA,j} VA_j^{\frac{\sigma-1}{\sigma}} + (1 - a_{VA,j}) E_j^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (4)$$

The value-added factors, labour and capital, are combined with a CES function, with elasticity values specific to each sector j .

$$VA_j = \left(a_{L,j} L_j^{\frac{\sigma-1}{\sigma}} + (1 - a_{L,j}) K_j^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (5)$$

Where α_j is the benchmark share of returns to labour for each sector j , and $(1 - \alpha_{L,j})$ is the remainder share, returns to capital. Total Labour and Capital supply are exogenous, and the factor prices are endogenous.

E_j is the energy good, a CES combination of direct fossil-fuel energy and electricity, each of which are composite goods from CES nests.

$$E_j = \left(a_{FE,j} FE_j^{\frac{\sigma-1}{\sigma}} + (1 - a_{FE,j}) EL_j^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (6)$$

Where FE_j is the demand for direct fossil fuel energy, a CES combination of the oil and gas, and EL_j is the electricity energy input, a composite of renewable generation (which includes solar, wind, hydro, and also nuclear), and fossil-fuel generation, which itself combines coal and gas generation.

$$FE_j = \left(a_{FEoil,j} FEoil_j^{\frac{\sigma-1}{\sigma}} + (1 - a_{FEgas,j}) FEgas_j^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (7)$$

$$EL_j = \left(\alpha_{Er} E_r + (1 - \alpha_{Er}) \left(\alpha_{Ecoal} E_{coal}^{\frac{\sigma-1}{\sigma}} + (1 - \alpha_{Ecoal}) FE_{gas}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (8)$$

This nesting structure allows firms to respond to the tax-inclusive prices of fossil fuels by switching from direct fossil fuel energy to electricity, from fossil electricity to renewables, and between the fossil fuels relative to their carbon intensity as the carbon tax changes relative costs.

2.1.a Behavioural Responses to Greenhouse Gas Taxes

I detail the structure of emissions and each tax in the model immediately below before illustrating the overall response to the imposition of either or both taxes.

Carbon Tax

The cost of energy inputs includes an economy-wide carbon tax on the fossil fuels used for energy production. The tax is set in proportion to the average carbon emission intensity of each fossil fuel.

The tax is applied at the point of the fossil fuel inputs into production, capturing both direct energy use and fossil fuels as an input to electricity generation.

$$c(E_f) = p_{E_f}(1 + \tau_{f,CO_2})E_f \quad (9)$$

Where the index f is a vector of the three fossil fuel types {coal, oil, gas}, p_{E_f} is the price of the fossil fuel input net of the carbon tax, τ_{f,CO_2} is the tax per unit of fossil energy inputs, and E_f is the quantity of the fossil fuel input demanded. The carbon tax rate is adjusted relative to the carbon emission intensity of each fossil fuel.

The cost of energy includes electricity generated from both fossil fuel and non-emitting sources. Therefore, the cost of the energy input includes the cost of direct oil- and gas-powered energy, each taxed relative to its emissions intensity, and the cost of electricity.

$$c(E_j) = p_{E_{oil}}(1 + \tau_{CO_2,oil})E_{oil} + p_{E_{gas}}(1 + \tau_{CO_2,gas})E_{gas} + c(EL) \quad (10)$$

The cost of electricity, $c(EL)$, incorporates the cost of coal generation (taxed relative to its emissions intensity), gas generation (taxed relative to its emissions intensity), and non-emitting generations which is not subject to the carbon tax.

$$\begin{aligned} c(EL) &= p_{EL} \cdot EL \\ &= p_{EL_{rnw}}EL_{rnw} + p_{E_{coal}}(1 + \tau_{CO_2,coal})EL_{coal} + p_{E_{gas}}(1 + \tau_{CO_2,gas})EL_{gas} \end{aligned} \quad (11)$$

Where EL_{rnw} is renewable and other non-emitting electricity generation, EL_{coal} and EL_{gas} are coal and gas-powered electricity generation. Initial prices $p_{EL_{rnw}}$, $p_{E_{coal}}$, and $p_{E_{gas}}$, and initial quantities of EL_{rnw} , EL_{coal} , and EL_{gas} , are from the baseline data, and change endogenously in response to the tax and other simulations. The electricity good EL is a single composite good with a single endogenous price, P_{EL} .

For each fossil fuel, the carbon tax rate incorporates a carbon intensity factor as follows:

$$\tau_{CO_2,f} = TR_{CO_2} \times CO_2factor_f \quad (12)$$

TR_{CO_2} is the overall carbon dioxide tax rate in \$/t of CO_2 emissions, and $CO_2factor_f$ is the intensity of emissions per unit of fossil fuel inputs for each fossil fuel type f .

$$CO_2factor_f = \frac{\sum \overline{Em}_f}{\overline{p}_{E_f} \sum \overline{E}_f} \quad (13)$$

Where $\overline{Em}_f$ is the total emissions of the fuel from the benchmark data in Billions of metric tons ($MMt \times 10^{-3}$), divided by the total cost of that fossil fuel input (price x total quantity) from the benchmark data in Billions US\$.

Methane Tax

The cost of the value-added inputs (labour and capital) for production includes a methane tax on the emissions from each sector¹². The tax is set in proportion to the average methane emission intensity for each sector. The tax is applied at the point of the value-added inputs to capture the choice that firms can make to reduce emissions intensity through expenditures on additional equipment (for example biogas digester) or labour (for example leak inspections).

The final term in equation (1), $c(VA_j)$, is the cost function for the value-added combined factor for each sector j . For non-methane-emitting sectors, the cost function is just the quantity of value-added inputs times the price. For methane-emitting sectors, emissions are linked to the value-added inputs, and $c(VA_j)$ is a step function where firms choose a level of direct methane abatement. Direct abatement reduces the methane intensity of a firm's activities, but at a cost of additional value-added inputs. Firms minimize costs by paying for abatement up to the point where it is more cost effective to reduce production and/or pay the methane tax¹³.

$$c(VA_j) = \min\{p_{va} \times VA_j \times Ab_{j,A} \times (1 + f(Int_{CH_4,j,A}) * TR_{CH_4})\} \quad \forall A \quad (14)$$

Where p_{va} is the value-added price, and VA_j is the quantity of value-added factors for each sector j .

$Ab_{j,A}$ is the abatement input factor for firm j which increases at every abatement level A .

$f(Int_{CH_4,j,A})$ is the CH_4 intensity factor per firm j which decreases with every abatement level A .

The CH_4 intensity factor adjusts the methane tax TR_{CH_4} (\$/t CH_4 ¹⁴) so it is proportional to the (mitigated) methane intensity of each firm's activity .

With no abatement, the CH_4 intensity factor evaluates as total benchmark CH_4 emissions from sector j over the total benchmark value-added input cost for sector j .

$$f(Int_{CH_4,j}) = \frac{\sum \overline{CH_4_j} (MMt) \times 10^{-3}}{p_{va} \sum \overline{VA_j} (BillUS\$)} = \frac{CH_4_j (t)}{VA_j (\$)} \quad (15)$$

With each level of abatement A , I subtract the quantity of emissions abated and add the additional quantity of value-added inputs for abatement.

$$f(Int_{CH_4,j,A}) = \frac{[CH_4_j - abated\ tons]}{p_{VA}[VA_j + abatement\ inputs]} = \frac{CH_{4,j,A} (t)}{VA_{j,A} (\$)} \quad \forall A \quad (16)$$

¹² There are six sectors with endogenous methane emissions (agriculture, waste, coal, gas, oil, and gas pipelines), representing 100% of methane emission from the GHG Inventory.

¹³ The value-added cost function is implemented with a complementarity structure. I establish a full set of potential value-added activities for each firm, each with different costs and emissions intensities. Only the specific value-added activities that allow a non-negative profit will be engaged. All other value-added abatement cost options will remain slack, evaluate to 0, and will not be activated in the model. The step function with the complementarity equation structure allows us to directly incorporate the EPA non-CO₂ marginal abatement cost data without additional manipulations or assumptions.

¹⁴ Methane is measured in the standard CO₂ equivalent (CO₂eq) unit, for all references and data in the model.

The numerator decreases with abatement levels and the denominator increases, reducing methane intensity. The abatement input factor increases in parallel.

Each step reduces methane emissions intensity as the abatement levels A go up and increases costs according to sector-specific Marginal Abatement Cost (MAC) curves. The abatement steps follow a cumulative marginal abatement curve, summing tiers of additional emissions abatement at marginally increasing abatement cost per unit of emissions mitigated¹⁵, starting at zero abatement — the benchmark level of emissions with benchmark value-added costs — through increasing tiers of mitigation amounts at mitigation costs from up to \$5/t through to \$1000/t.

Firm Response to the Imposition of GHG Taxes

The firm responds to the GHG taxes by substituting away from the inputs that are intensive in the relevant emissions.

In the case of carbon tax, in particular, firms reduce the emission-intensive inputs as their prices rise, and reduce production, to the point that it becomes cost efficient to pay the carbon tax. There is no direct technological abatement for carbon emissions in the model.

The firm simultaneously minimizes costs by responding to the methane tax with substitution away from the emissions-intensive value-added activity, undertaking methane abatement, reducing production, and paying the methane tax for the remaining emissions.

The overall unit cost function to produce a unit of good Y_j as a function of inputs, the CO_2 tax, the CH_4 tax, and abatement costs is given by:

$$c_j(PA_{i,j}, \tau_{CO_2}, \tau_{CH_4}, A_{j,m}) = \min \left\{ \sum_{i=1}^I p_{a_i} ID_i + CH_4 Int_{VA,j} \times \{p_{va} \times VA_j \times Ab_{j,m} (1 + \tau_{CH_4}) + \right. \\ \left. CO_2 Int_{ff} \times p_{ff} \times FF_j \times (1 + \tau_{CO_2}) + \right. \\ \left. CO_2 Int_{el} \times p_{elec} \times Elec_j \times (1 + \tau_{CO_2}) \mid f_j(\sum_i ID_i, VA_j, E_j) \geq 1 \right\} \quad (17)$$

As detailed above, input demand for production follows a nested structure, and so the closed form expression for the cost function is given by:

¹⁵ Methane mitigation amount (and cost) includes all tons and total weighted costs of mitigation up to that tier from the EPA's CO_2 Marginal Abatement Curve report. Weighting accounts for quantities of mitigation at each tier mitigation costs. Tiers (in 2017US) \$are: < -\$20, < -\$10, < -\$5, < \$0, < \$5, < \$10, < \$15, < \$20, < \$30, < \$40, < \$50, < \$100, < \$500, < \$1,000. Costs were adjusted from 2017US\$ to 2022US\$ with BLS CPI data. Negative cost tiers are incorporated into the cumulative costs, but only tiers with cumulative costs > 0 are included.

$$C_j^* = \left[\alpha_{ID} \cdot \left(\sum_{i=1}^I p a_i \right)^{\sigma-1} + \alpha_{vae} \cdot \left(\alpha_{va} \cdot \left(Ab_{j,m} \cdot pva_j \cdot (1 + \tau_{CH_4} \cdot CH_4 Int_{VA,j}) \right)^{\sigma_{VAE}-1} + \alpha_E \cdot \left(\alpha_{ff} \cdot \left(p_{ff} \cdot (1 + \tau_{CO_2} \cdot CO_2 Int_{ff}) \right)^{\sigma_E-1} + \alpha_{el} \cdot \left(CO_2 Int_{el} \cdot p_{elec} \cdot (1 + \tau_{CO_2}) \right)^{\sigma_E-1} \right)^{\frac{\sigma_{VAE}}{\sigma_E}} \right)^{\frac{\sigma-1}{\sigma}} \right] \quad (18)$$

The first order conditions for each input at each level of the nest show the point at which the marginal cost of the input must meet its marginal value for minimum cost. Combining the first order conditions of each input gives us the optimal ratio as a function of the prices.

For instance, from the Lagrangian, the first order conditions that give us the optimal demand ratio for energy and value-added of the nest VAE is given by:

$$\frac{VA_j}{EN_j} = \left(\frac{\alpha_{VA,j}}{\alpha_{EN}} \right)^{\sigma_{VAE}} \cdot \left(\frac{p_{VA}(1 + \tau_{CH_4} \cdot CH_4 Int_{VA})}{p_{EN}(1 + \tau_{CO_2} \cdot CO_2 Int_{EN})} \right)^{-\sigma_{VAE}} \quad (19)$$

From the first order conditions for any element of a CES nest, I get the optimal demand per unit of the nest's composite. For instance, VA in the composite VAE.

$$\frac{VA_j}{VAE_j} = \frac{\alpha_{VA,j}^{\sigma_{VAE}} [p_{VA}(1 + \tau_{CH_4} \cdot CH_4 Int_{VA})]^{-\sigma_{VAE,j}}}{P_{VAE}} \quad (20)$$

Where p_{VAE} is the price of the nest's output as given by:

$$P_{VAE} = \alpha_{VA,j}^{\sigma_{VAE}} [p_{VA}(1 + \tau_{CH_4} \cdot CH_4 Int_{VA})]^{-\sigma_{VAE,j}} + \alpha_{EN,j}^{\sigma_{VAE}} [p_{EN}(1 + \tau_{CO_2} \cdot CO_2 Int_{EN})]^{-\sigma_{VAE,j}} \quad (21)$$

Ultimately, the optimal quantity of any element in the production of a unit Y from sector j is the optimal quantity at each nest level, times the optimal quantity of that nested input in that nest's composite output, up through all branches of the nested tree. With fossil fuel gas inputs as an example¹⁶, with my nested structure, the optimal quantity of gas as an input gas in production of a unit of Y in sector j is

¹⁶ The gas input is slightly more complicated than other fossil fuel inputs because it appears as an input for both direct fossil energy and electricity.

$$FE_{gas}^* = \left(\left(\left(\frac{FE_{gas}}{E_{FE}} \cdot \frac{E_{FE}}{E_{EN}} + \frac{E_{gas}}{E_{EL}} \cdot \frac{EL}{EN} \right) \cdot \frac{EN}{VAE} \right) + \frac{VA}{VAE} \right) \cdot \frac{VAE}{Y} \cdot Y \quad (22)$$

And for the other two fossil fuel input, oil and coal:

$$FE_{oil}^* = \left(\frac{FE_{oil}}{E_{FE}} \cdot \frac{E_{FE}}{E_{EN}} \cdot \frac{EN}{VAE} + \frac{VA}{VAE} \right) \cdot \frac{VAE}{Y} \cdot Y \quad (23)$$

$$FE_{coa}^* = \left(\frac{E_{coa}}{E_{EL}} \cdot \frac{EL}{EN} \cdot \frac{EN}{VAE} + \frac{VA}{VAE} \right) \cdot \frac{VAE}{Y} \cdot Y \quad (24)$$

And then expanding with the first order conditions of each nest for the example of fossil gas, the optimal quantity of gas demanded by sector j in its production of a unit of Y is given by:

$$\begin{aligned} FE_{gas_j} = & \left(\left(\alpha_{gas_j}^{\sigma_{FE_j}} \left[\frac{p_{gas}(1+\tau_{CO_2} \cdot CO_2 Int_{gas})}{P_{FE}} \right]^{-\sigma_{FE_j}} \cdot \alpha_{FE_j}^{\sigma_{EN_j}} \left[\frac{p_{FE}}{P_{EN}} \right]^{-\sigma_{EN}} \right. \right. \\ & + \alpha_{gas_j}^{\sigma_{EL_j}} \left[\frac{p_{gas}(1+\tau_{CO_2} \cdot CO_2 Int_{gas})}{P_{EL}} \right]^{-\sigma_{EL_j}} \cdot \alpha_{EL_j}^{\sigma_{EN_j}} \left[\frac{p_{EL}}{P_{EN}} \right]^{-\sigma_{EN}} \left. \right) \cdot \alpha_{EN}^{\sigma_{VAE_j}} \left[\frac{p_{EN}}{P_{VAE}} \right]^{-\sigma_{VAE_j}} \\ & + \alpha_{EN_j}^{\sigma_{VAE_j}} \left[\frac{p_{VAM} \cdot Ab_m \cdot (1+\tau_{CH_4} \cdot f(CH_4 Int_m))}{P_{VAE}} \right]^{-\sigma_{VAE_j}} \cdot \alpha_{VAE_j}^{\sigma_{Y_j}} \left[\frac{p_{VAE}}{P_Y} \right]^{-\sigma_{Y_j}} \cdot Y_j \end{aligned} \quad (25)$$

This shows that the firm decision to determine the quantity of fossil fuel gas is a function of its price inclusive of the CO₂ tax, and simultaneously inclusive of the CH₄ tax as part of the value-added input. As above, the tax-inclusive price of the VA input depends on methane intensity, which decreases with abatement. At the same time, abatement cost increases with abatement. So responding to the methane tax, firms are balancing the cost of abatement against the reduced tax burden from mitigating the methane intensity of their activities.

2.1.b Foreign Trade

A representative firm for each sector j maximizes revenue by choosing between selling domestically or for export. Firms also minimize costs of inputs by choosing between domestically produced goods net of taxes and subsidies, and imports net of tariffs in an Armington CES function, along with a fixed proportion cost of trade and transport.

$$\pi_j = pa_j A_j + pfx \times X_j - py_j Y_j - pfx \times M_j(1 + \tau_M) - pm_j T_j \quad (26)$$

The first two terms on the right are the revenue from domestic and export sales, and the following three terms subtract the costs of domestic inputs, imports with an import tariff, and the combined costs of trade and transport margins.

Firms choose how much to supply for either the domestic market or exports with a Constant Elasticity of Transformation function.

$$A_j = \left(\beta D_j^{\frac{\eta+1}{\eta}} + (1 - \beta) X_j^{\frac{\eta+1}{\eta}} \right)^{\frac{\eta}{\eta+1}} \quad (27)$$

Where D_j is the supply to the domestic market, and X_j is the supply for export.

Inputs are combined in a nested production function. At the top level, the Armington good is combined with the trade and transport costs in a fixed, Leontief function proportion.

$$Y_j = \min \left(\frac{A_j}{a_{A_j}}, \frac{Tr_j}{a_{Tr_j}} \right), \quad \alpha_{A_j}, \alpha_{Tr_j} > 0 \quad (28)$$

Where A_j is the Armington intermediate input good for sector j , and a_{A_j} is the share factor of the Armington good from the baseline data, Tr_j is the combination of the trade and transport margin for sector j , and α_{Tr_j} is the share coefficient for the combined trade and transport margins.

The Armington good is a combination of the domestic version of the good for sector j and the import version of the good, as imperfect substitutes according to a Constant Elasticity of Substitution function.

$$A_j = \left(\alpha Y_j^{\frac{\sigma-1}{\sigma}} + (1 - \alpha) (M_j)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \quad (29)$$

The balance of payments is fixed at the benchmark level, and the price of foreign exchange, PFX, adjusts.

2.3 Household Behaviour

The representative consumer gets utility from consumption of private and public goods and services supplied to the domestic market as in equation (27), representative commodities from each of 76 sectors in the model. Utility follows a nested CES function as follows:

$$U = \left(\sum_{i=1}^N a_i D_i^{\frac{\sigma_i-1}{\sigma_i}} \right)^{\frac{\sigma_i}{\sigma_i-1}} \quad \sum a_i = 1 \quad \forall i \quad (30)$$

Where each nest level i follows the CES functional form with an elasticity parameter σ_i and share parameter a_i . The share parameter tracks all goods included below nest i in the consumer's bundle from the benchmark data. The composite commodity combined at each nest level become the inputs for the level above. The nesting structure follows Figure 3 below. All 76 representative commodities are grouped into the relevant categories as shown in the figure.

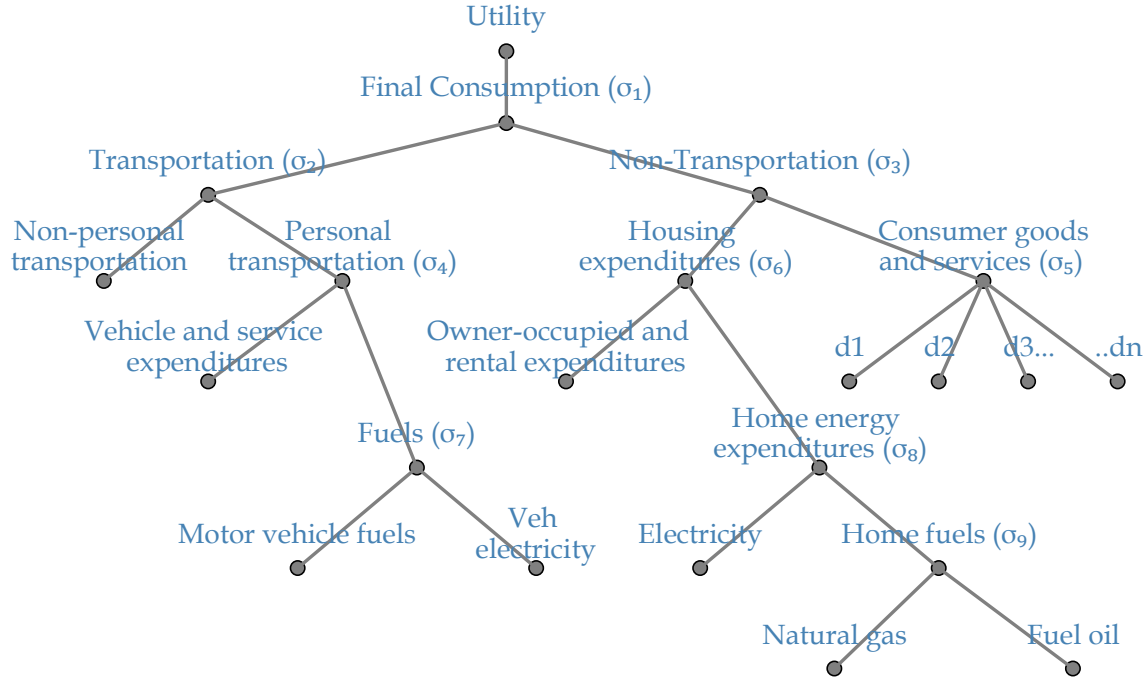


Figure 3: Nesting structure for the representative household's consumption utility

The representative household maximises their utility subject to the budget constraint:

$$\sum pva_j VA_j + BOP - Inv_j + total\ taxes - \sum pa_j D_j = 0 \quad (31)$$

where VA_j is the combination of labour and capital provided to sector j , at price pva_j , BOP is the balance of payments deficit (the total value of goods and services imported above the total value exported), Inv_j is expenses on infrastructure, equipment, inventory etc. and is fixed at the benchmark level. Net taxes are passed as a lump-sum transfer to the representative household consumer, contributing to their income and the purchase of all goods and services. Taxes include output taxes, import tariffs, taxes net of subsidies on intermediate demands, and the CO_2 and/or CH_4 taxes in the greenhouse gas tax simulations. pa_j is the price of the good D_j from sector j .

The primary factors in the model are endowments of labour and capital, in fixed supply, with endogenous prices. Both labour and capital are fully mobile between sectors.

2.4 Solving the model

The model is structured to satisfy competitive market equilibrium conditions which can be classified into Market Clearance and Zero Profit, along with the Income Balance constraint as follows:

2.4.a Market Clearing Conditions

All commodities that are produced and factor commodities which enter the economy are fully utilized, that is, supply meets demand. There are 234 individual commodities with prices that adjust in response to the imposition of GHG taxes, each with an associated market clearance equation that ensures the condition is met. There are 76 intermediate production commodities; the labour and

capital factor commodities; trade and transport margins commodities; 76 trade/final demand commodities; a foreign exchange price; 76 sector-specific value-added factors which mechanically combine labour and capital prices for each sector; and a single final utility good.

2.4.b Zero Profit Conditions

All firms are competitive; the total value of all inputs and taxes equals the total value of all outputs minus taxes for each firm, and no firms make a positive profit. There are 284 representative firms/sectors undertaking production, trade, and transport. There are 76 production sectors; 73 trade sectors; trade and transport margins sectors; a set of 76 value-added activities; a final demand ‘sector’ that produces utility; and a set of potential methane-abatement value-added activities that are initially unprofitable and unused in the benchmark.

2.4.c Income Balance Constraint

The total value of labour, capital, balance of payments, and received taxes from the representative household equals the total value of consumption and investment for the representative household.

The benchmark value of the basket of final demand goods demanded by the representative consumer serves as the numeraire.

2.4.d Equilibrium

Solving the model in the absence of any new climate policy replicates the benchmark data. Each price and economic activity has an associated equation which together define the full set of equilibrium conditions and constraints. As any change is introduced - in this case any climate policy - all prices and quantities in the model adjust to ensure that the equilibrium conditions for all commodities and sectors are met, and that the representative consumer budget is balanced. Representative firms and the representative consumer respond to GHG reduction policies by substituting among alternative inputs, undertaking direct abatement, and altering production and consumption decisions.

The model is constructed as a Mixed Complementarity Problem (MCP) which allows for non-profitable economic activities to be dormant. All prices and sector activity levels are interdependent and must be solved for simultaneously to arrive at the new equilibrium. A numerical algorithmic solver (PATH) finds the set of solutions to all equations that simultaneously satisfies all the required equilibrium conditions.

2.4.e Data

The primary, balanced and calibrated CGE data comes from the Wisconsin National Data Consortium (WiNDC) (Rutherford and Schreiber 2019), via the WiNDC.jl Julia package. The summary set of sectors was disaggregated to separate coal from other mining, and to separate ‘utility’ into ‘electric’, ‘gas’, and ‘waste’. The balanced WiNDC dataset is built from the BEA (Input/Output tables, GDP, Personal Consumption Expenditures), the US Census Bureau’s Trade data, and the Bureau of Transportation Statistics. WiNDC data are available for all the years 1997 through to 2022.

The BEA economic data for the ‘oil and gas’ sector and commodity, and the ‘electricity generation and distribution’ sector and commodity were disaggregated into separate ‘oil’, ‘gas’, ‘fossil electricity’ and ‘renewable electricity’ using ratios calculated from EIA data.

CO₂ emissions by sector, and data from for the fossil fuel emissions factors are from the EPA 2024 Greenhouse Gas Inventory Report.

Data on CH₄ emissions by sector, and the marginal abatement costs are from the Global Non-CO₂ Greenhouse Gas Emission Projections & Mitigation project from the EPA’s Office of Atmospheric Programs. Methane emissions in the base data and my model are measured in the unit of CO₂ equivalence (CO₂eq). The EPA data in this analysis uses the common 100-year comparison period, with a Global Warming Potential (GWP) of 25, meaning 25 times the GWP of an equivalent mass of CO₂ over 100 years. I adjust the GWP parameter in an alternative specification.

Emissions in the model represent 86% of total gross U.S. greenhouse gas emissions in 2022. CO₂ emissions from fossil fuel combustion in the model constitute 93% of all CO₂ emissions. CH₄ emissions from fossil fuel activities, agriculture, and waste represented in the model constitute 99% of total CH₄ emissions reported. Emissions intensities are calculated directly from the data as total emissions per sector over total value of the input in production.

Table 2: Emissions of each GHG within each fossil fuel sector in the benchmark data

	CO ₂ Emissions MMt ¹⁷	CH ₄ Emissions MMt CO ₂ eq ¹⁸	CH ₄ as a % of both GHGs in the model
Oil	2,115	44	2.0%
Gas	1,741	177 ¹⁹	9.2%
Coal	896	44 ¹⁹	4.6%

2.4.f Parameters

Share parameters for the input and output production nests reflect the base economic data for the year 2022 as represented in the calibrated WiNDC economic data.

The CES elasticity parameter values are sourced from: the EPA’s SAGE model (Marten et al. 2024) which empirically estimated substitution elasticities at each nest level following (Antoszewski 2019), use and report values from GTAP for the Armington elasticities, and reference (Caron and Rausch 2013) for the CET value; and the E3 model (Goulder and Hafstead 2018) for the CES values which are used in the materials input nest, and the energy nests. In order to link the 76 sectors to the 23 sectors used in the 2.1.1 SAGE model, and the 35 sectors in the referenced E3 model, a concordance table was generated using the associated NAICS codes. The elasticity parameter values and the nesting structure for the nested CES utility of demand are sourced from the E3 model which are adapted from (Ross 2014).

¹⁷ EPA GHG Inventory 2024, table 1-4: Oil [248 industrial, 1681 transport, 65 commercial, 62 residential, 21 electricity, 17 U.S. territories]; Gas [659 electricity, 510 industrial, 272 residential, 192 commercial, 37 natural gas systems, 70 transports]; Coal [852 electricity, 43 industrial, 1 commercial].

¹⁸ EPA Non-CO₂ MAC model data: Oil and Gas split from “GAS” by value of intermediate output.

¹⁹ includes ½ gas/oil wells, 4.25 MMt

The value used for the social cost of greenhouse gases is from the EPA social cost of CO₂ for 2022, with the central 2% near-term discount rate. The value is reported as \$200 in 2020US\$ and I adjust for inflation²⁰ to \$226.10/t. All methane emissions and abatement cost data in the model is in the unit of CO₂eq, so the same SCCO₂ is used for both greenhouse gases.

The tax rates for each type of greenhouse gas are adjustable parameters in the model, allowing for various specifications and greenhouse gas tax rate scenarios.

3. Policies

I examine a set of policies for mitigating GHGs, consisting of taxes³ on CO₂ and CH₄, individually and in combination. Taxes are set proportional to the emissions intensity of the primary inputs in the case of carbon, and proportional to the intensity of emitting activities in the case of methane. This allows for emissions, emission intensities, and tax and abatement costs to disseminate and adjust throughout the economy and the supply-chain including final consumption.

With my static, single-year model, I am simulating instantaneous policies applied on a baseline of the economy and emissions as they were in the year 2022²¹. The static structure does not incorporate dynamic factors such as transition costs, productivity and structural changes, or forward-looking considerations, but the central qualitative lessons would likely hold in a dynamic model.

3.1 Carbon Tax

I examine an economy-wide tax on all endogenous carbon dioxide emissions from fossil fuel combustion. I apply the tax to the fossil fuels at the point of extraction, proportional to the total emissions intensity²² of each fuel (coal, oil, and gas).

3.2 Methane Tax

3.2.a Economy-wide Methane Tax

Separately, I impose an economy-wide methane emissions tax²³. The tax is applied to the major CH₄ emitting sectors, proportional to the methane emissions intensity of activities in each sector.

3.2.b Sector-specific Methane Tax

I investigate the impacts of sector-specific policies for methane reduction.

²⁰ U.S. Bureau of Labour Statistics annual Consumer Price Index.

²¹ I impose policies on a baseline representation of the U.S. economy and emissions in 2022 which had existing GHG reduction policies in place at the state and local level. A number of states had reduction targets, several with forms of carbon pricing, electricity emissions standards etc. e.g. <https://www.c2es.org/content/state-climate-policy/> Other extant state and local policies were contributing to emissions reductions, including local waste and air pollution regulation etc.

²² As in equation 13 above, emissions intensity for each fossil fuel type is total emissions for the fuel source in GMt CO₂ divided by total intermediate demand in billions \$US.

²³ As described in the 2.4.e Data section above, methane emissions are modeled in the CO₂eq unit. Therefore, the tax rate should also be interpreted as \$/t CO₂eq, and the SCCO₂ is used for the Social Cost of Methane.

Recent U.S. methane policy under the Inflation Reduction Act focused on reductions from the oil and gas sector. In the U.S., the Inflation Reduction Act included a number of methane mitigation provisions focused on the oil and gas sector: \$1.36 Billion for technical and financial assistance as part of the Methane Emissions Reduction Program; a fee for large emitters in the oil and gas sector starting at \$900/t in 2024 and increasing to \$1,500/t by 2026; updated performance standards under the Clean Air Act; updates to reporting; and a program to enable certified 3rd parties to report ‘super-emitters’²⁴. Other federal programs focus on landfills and agriculture to a lesser extent, along with programs and regulations from states and other levels of government.

To represent that policy, I impose a methane tax as immediately above, but restricted to the oil, gas, and pipeline sectors only.

3.3 Combination of Carbon Tax and Methane Tax

In addition to considering carbon and methane taxes separately, I examine the two types of taxes in combination.

3.3.a Combination of Economy-wide Carbon Tax and Sector-specific Methane Tax

I undertake the exercise outlined immediately above, restricting the methane tax to only the gas, oil, and pipeline sectors.

With greenhouse gas taxes implemented endogenously in the model as described above, the results illustrate how CO₂ and CH₄ policies, and the interactions between them, shape economic and emissions outcomes.

4. Results

In Section 4.1 below, I introduce an extended general equilibrium Pigouvian framework for a second-best setting in which two jointly produced pollutants generating a single externality are not both taxed at their full Pigouvian rates. In this setting, taxing either pollutant at its marginal social cost fails to internalize the associated externality from the other. First, I show how fully Pigouvian taxes on both carbon and methane emissions reduces emissions in the model for reference. Then, I show the tax levels that internalize the combined climate externality across both gases in the second-best setting. Accounting for general equilibrium interactions, emissions of the two endogenous GHGs respond as complements to mitigation policy. Lowering either tax increases emissions of both GHGs economy-wide; raising either tax decreases both emissions. With emissions positively correlated, the extended general equilibrium Pigouvian tax rates that account for the associated emissions across the two major GHGs are higher than standard Pigouvian rates.

²⁴ Super-emitters defined as emitting at a rate of more than 100 kilograms of methane per hour

In section 4.2, I present results for a cost-effectiveness analysis. To provide a consistent basis for cost comparison, I evaluate a set of policies achieving the same total greenhouse gas reduction target. I determine the carbon tax rate that achieves the target, including the complementary reductions of methane. Then I determine the methane tax rate that achieves the target, including the complementary reductions of carbon. Finally, I assess the welfare cost along a set of combined carbon and methane tax rates that meet the reduction target.

Section 4.3 presents the emissions response and welfare cost of the set of central policy scenarios.

In section 4.4, I examine a set of alternative specifications to assess key parameter and assumption sensitivities.

4.1 Pigouvian Taxes and Extended General Equilibrium Pigouvian Rates

The social costs of greenhouse gases evaluate the impact of climate damages from a marginal quantity of greenhouse gas emissions. They measure the monetized climate externality cost of an incremental amount of emissions in present value terms. In general, they are assessed as the impact of adding a (marginal) ton of a specific greenhouse gas to the atmosphere, assuming all else equal, including the emissions of other greenhouse gases²⁵.

4.1.a Optimal First-Best: Combined Pigouvian Carbon and Methane taxes

A first-best, fully optimal Pigouvian policy imposes taxes on all GHGs at their social costs. Setting pollution taxes to internalize the externality in this way ensures that the additional social cost will propagate throughout decisions in the economy (Nordhaus 2019). With both taxes set at their social costs, economic agents will fully internalize the combined externality of both major GHGs, generating the theoretically optimal outcome. Emissions will decline as decision-makers respond to higher emission-related costs and the lower relative costs of commodities with less associated emissions. Any remaining emissions will only occur if the associated marginal benefits exceed the total marginal cost, including both the private and internalized social costs.

Table 3 below shows the emission reductions from the fully optimal Pigouvian taxes as simulated by the model.

²⁵ For example, the social cost of carbon dioxide (SCCO₂) and the social cost of methane (SCCH₄). Note that the term social cost of carbon (SCC) is sometimes also used as shorthand to mean the social costs of carbon dioxide, but also used to mean the social cost of emissions expressed per ton of carbon.

Table 3: Pigouvian greenhouse gas tax rates

Baseline endogenous emissions (MMt CO ₂ eq)	GHG: 5,447 CO ₂ : 4,752 CH ₄ : 695
Policy	Pigouvian first-best
CO₂ tax level	\$226/t (SCCO₂)
CH₄ tax level (CO₂eq)	\$226/t (SCCH₄)
Total GHGs reductions, MMt CO ₂ eq (% of baseline GHGs)	3,331 (61%)
CO ₂ reductions, MMt (% CO ₂)	2,973 (63%)
CH ₄ reductions, MMt CO ₂ eq (% CH ₄)	358 (51%)

Second-Best: Extended General Equilibrium Pigouvian taxes on Carbon

In a second-best climate policy setting, where not all greenhouse gases are taxed at their Pigouvian rates, a Pigouvian tax on a single GHG set at the social cost does not internalize the climate damages from associated co-produced gases. I address this issue with extended general equilibrium (GE) Pigouvian rates that adjust each tax to account for the climate damages of the complementary gas, capturing the full joint social cost of these co-produced emissions.

4.1.b Second-Best: Extended General Equilibrium Pigouvian taxes on Carbon

To determine the extended general equilibrium Pigouvian tax rate for carbon, I first set the carbon tax to the social cost of carbon dioxide²⁶ (SCCO₂) and evaluate the level of co-produced CH₄ emissions. I then adjust the tax rate to account for those associated CH₄ emissions, with the damages of each ton of CH₄ valued at the social cost of methane (SCCH₄).

The adjusted extended general equilibrium Pigouvian carbon tax rate is then:

$$\tau_{CO_2}^* = SCCO_2 + \Delta CH_4(\tau_{CO_2}) \times SCCH_4 \quad (32)$$

Where $\Delta CH_4(\tau_{CO_2})$ is the proportion of CH₄ emissions associated with the CO₂ reductions from a carbon tax set at the SCCO₂. The abatement response mirrors the production relationship: reducing the tax induces increases of both GHG in the same proportion.

With a tax on CO₂ set to the SCCO₂, the model indicates an additional 5% of associated CH₄ reductions, reflecting the overlap in economic activities generating both GHGs. Table 4 below reports the extended general equilibrium Pigouvian tax rate for carbon, accounting for the climate externality of associated CH₄ emissions. A standard Pigouvian tax set at the social cost of carbon is shown for comparison.

²⁶ All methane emissions data in the model are in the CO₂ equivalent unit. I therefore use the EPA SCCO₂ value for the year 2022 (EPA 2023), adjusted for inflation.

Table 4: Extended general equilibrium Pigouvian tax rate for carbon dioxide compared to the standard Pigouvian tax set at the social cost of carbon dioxide

Baseline endogenous emissions (MMt CO ₂ eq) GHG: 5,447 CO ₂ : 4,752 CH ₄ : 695		
Policy	CO ₂ tax: Extended GE Pigouvian	CO ₂ tax: Standard Pigouvian
CO₂ tax level	\$237/t	\$226/t (SCCO₂)
CH₄ tax level (CO₂eq)	-	-
Total GHGs reductions (MMt CO₂eq)	2,904	2,846
CO ₂ reductions (MMt)	2,774	2,719
CH ₄ reductions (MMt CO ₂ eq)	130	127

Across all tested levels of a CO₂ tax in the model, the ratio of the CH₄ to CO₂ emission responses is relatively constant at around 5%.

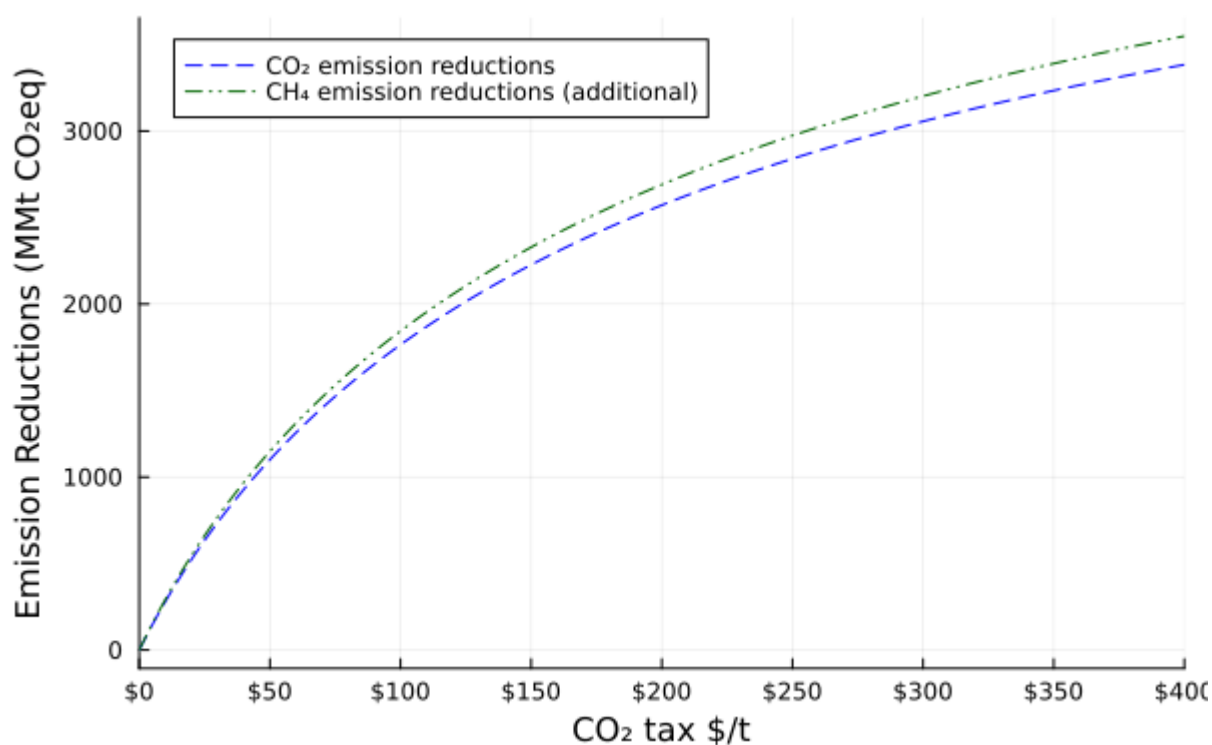


Figure 4: Emissions reductions in response to a carbon tax

Figure 4 above illustrates the reductions of both types of endogenous greenhouse gases in response to increasing levels of a carbon tax. As the tax rate rises, carbon emissions decline. The concave shape shows the diminishing marginal effectiveness of the carbon tax. Methane emissions are also reduced, roughly in proportion to the reductions in carbon.

4.1.c Second-Best: Extended General Equilibrium Pigouvian tax on Methane

To determine the extended general equilibrium Pigouvian tax rate for methane, I set the methane tax to the Pigouvian level of the SCCH₄²³ and evaluate the level of co-produced CO₂ emissions. I then

adjust the tax rate to account for those associated CO₂ emissions, with the damages of each ton of CO₂ valued at the social cost of carbon dioxide (SCCO₂).

The adjusted extended general equilibrium Pigouvian methane tax level is then:

$$\tau_{CH_4}^* = SCCH_4 + \Delta CO_2(\tau_{CH_4}) \times SCCO_2 \quad (33)$$

Where $\Delta CO_2(\tau_{CH_4})$ is the proportion of CO₂ emissions associated with the CH₄ reductions from a tax on methane set at the SCCH₄. Again, the abatement response mirrors the production relationship: reducing the tax induces increases of both GHG in the same proportion.

With a tax on CH₄ set to the SCCH₄, the model indicates an additional 212% of associated CO₂ reductions, reflecting the overlap in economic activities generating both GHGs. Table 5 below reports the extended general equilibrium Pigouvian tax rate for methane, accounting for the climate externality of associated CO₂ emissions. A standard Pigouvian tax set at the social cost of methane is shown for comparison.

Table 5: Extended general equilibrium Pigouvian tax rate for methane compared to the standard Pigouvian tax set at the social cost of methane

Baseline endogenous emissions (MMt CO ₂ eq) GHG: 5,447 CO ₂ : 4,752 CH ₄ : 695		
Policy	CH ₄ tax: Extended GE Pigouvian	CH ₄ tax: Standard Pigouvian
CO₂ tax level	-	-
CH₄ tax level (CO₂eq)	\$705/t	\$226/t (SCCH₄)
Total GHGs reductions (MMt CO ₂ eq)	2,038	939
CO ₂ reductions (MMt)	1,624	638
CH ₄ reductions (MMt CO ₂ eq)	414	301

4.2 Cost-Effectiveness of Climate Policy

In order to compare the cost-effectiveness of different policies, I set a specific GHG reduction target and compare the welfare cost of achieving the same level of overall emission reductions under three different policy scenarios. First, I determine the carbon tax rate that would achieve the overall emission reduction target on its own. Second, I determine the methane tax rate that would achieve the overall emission reduction target on its own. Third, I conduct a simulation experiment that sets both taxes along a schedule of combined levels that meet the reduction target.

I assess the welfare cost for each of these three policy scenarios, measuring welfare cost as the equivalent variation²⁷ for the representative consumer in my model. For the combined policy simulation exercise, I assess the welfare cost at every point along the schedule. With a lump-sum

²⁷ Equivalent variation (EV) measures the change in utility in terms of the original prices. $EV = \% \Delta U \times \text{Income at original prices}$. In this way, I can quantify the difference in endogenous welfare even as all prices change. In my model, with utility as a CES function of consumption expenditures and benchmark prices set to 1, I also leave out the income measure, and report % change in utility as change in EV.

transfer of tax revenue — which is a feature of all policy simulations in this paper — equivalent variation tracks excess burden.

4.2.a Least-Cost Policy with economy-wide taxes

To enable a welfare-cost comparison evaluated against a consistent objective, I use the Paris Agreement target because of its salience as part of the multi-decadal process of international climate negotiations under the U.N. IPCC.

“...the United States is communicating an economy-wide target of reducing its **net greenhouse gas emissions by 61-66 percent below 2005 levels in 2035**. The entire 2035 range is on a straight line or steeper trajectory to net zero emissions by 2050 for all greenhouse gases”²⁸.

To meet the Paris target following a linear reduction path²⁹, total gross GHG emissions in 2022 would have needed to be 21% lower than they were. I use this 21% GHG reduction target for my policy experiment. Figure 5 below shows greenhouse gas emissions for the United States from 1990 to 2022, with a projection³⁰ from 2022 to the nationally determined contribution reduction target for 2035³¹.

²⁸ [https://unfccc.int/sites/default/files/2024-12/United States 2035 NDC.pdf](https://unfccc.int/sites/default/files/2024-12/United%20States%202035%20NDC.pdf)

²⁹ I calculate the additional reductions needed in 2022 to be on a linear path to meet a 61% reduction from 2005 levels by 2035. Assuming an approximately stable annual sink of -920 MMt from 2022, implies that gross emissions should be 3,491 MMt or less by 2035. Assuming a linear reduction from 2005 to achieve that target means an additional reduction of 1117 MMt from reported 2022 gross GHG emission levels.

³⁰ I extrapolate linearly from the most recently published data for 2022 to the conservative end of the range, 61% reduction below 2005 emissions. I assume the same percentage reduction for each of the four plotted greenhouse gases.

³¹ The U.S. emissions reduction target for 2035 is taken from [https://unfccc.int/sites/default/files/2024-12/United States 2035 NDC.pdf](https://unfccc.int/sites/default/files/2024-12/United%20States%202035%20NDC.pdf)

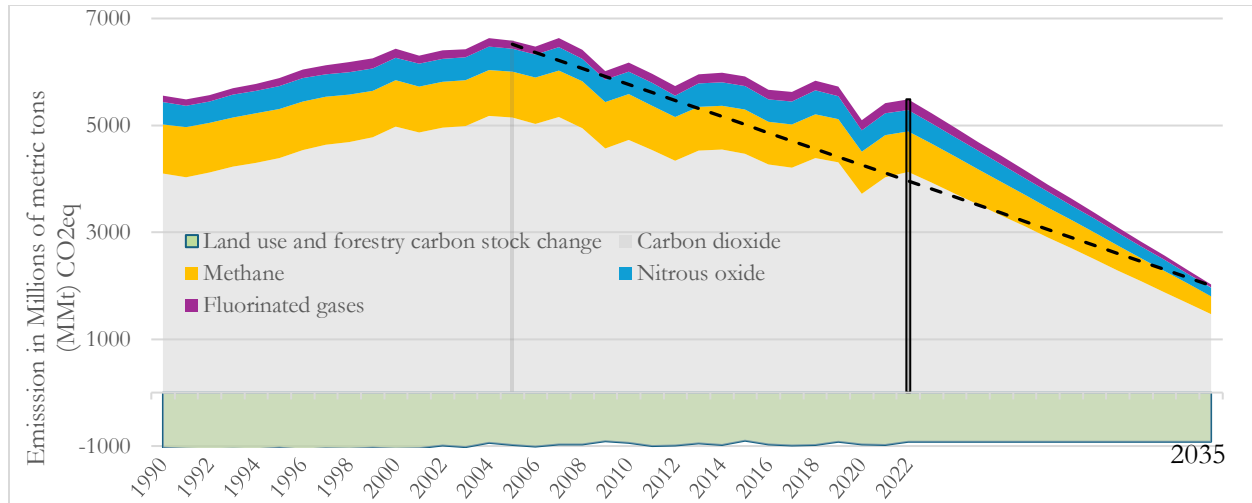


Figure 5: U.S. Greenhouse Gas Emissions with the Paris Agreement 2035 target³²

The grey vertical line marks 2005, the benchmark year of emissions for the Paris reduction target. The black vertical line marks 2022, the data year used for this paper, and the dotted black line marks the linear path to the Paris Agreement target.

The 21% Paris Agreement-aligned reductions are substantially smaller than the reductions produced by the model under the first-best Pigouvian combination of CO₂ and CH₄ taxes, the extended GE Pigouvian taxes for CO₂ or CH₄, and the CO₂ tax set to the SCCO₂³³. The Pigouvian rates internalize the cost of the global climate externality of emissions, implying emission reductions that are globally socially optimal. This suggests that a reduction to the linear path consistent with the Paris target falls far short of being welfare-optimal from a global perspective.

For reference, Table 6 below shows the 2022 emission reductions implied by the Paris Agreement target alongside the reductions generated by the model under the various Pigouvian tax scenarios described in the previous section.

³² Greenhouse gas emissions data is from the U.S. EPA
<https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allsectors/allgas/gas/all>, the same as for Figure 1

³³ The reductions under the CH₄ tax set to the SCCCH₄ are slightly lower than the Paris benchmark.

Table 6: Comparing Reductions between Paris Agreement and Pigouvian Tax rates

Baseline endogenous emissions (MMt CO ₂ eq) GHG: 5,447						
	Paris Target	First Best Pigouvian	Extended GE Pigouvian CO ₂ tax	Extended GE Pigouvian CH ₄ tax	Standard Pigouvian CO ₂ tax	Standard Pigouvian CH ₄ tax
Total GHGs reductions (MMt CO ₂ eq)	1,117	3,331	2,904	2,038	2,846	939
Percent of endogenous baseline emissions	21%	61%	53%	37%	52%	17%

Least-Cost Policy

To determine the most cost-effective policy, I assess the welfare cost of three scenarios. First I determine the level of an economy-wide carbon tax needed to meet the Paris Agreement-aligned reduction target. Second, I determine the level of an economy-wide methane tax needed to meet the Paris Agreement-aligned reduction target. Finally, I run an experiment simulating a full schedule of tax combinations that meet the target. Starting from the point at which the CO₂ tax level on its own achieves the target, I incrementally increase the CH₄ tax by an additional \$1/t and concomitantly decrease the CO₂ tax, such that the combination of taxes exactly meets the reduction target.

Table 7 below reports the results. The first and second columns show the welfare cost of using only the carbon tax or the methane tax to meet the reduction target. The final column shows the cost-minimizing point of combined carbon and methane tax policy stringencies.

Table 7: Policies that achieve Paris Agreement-aligned reduction target

Baseline endogenous emissions (MMt CO ₂ eq) GHG: 5,447 CO ₂ : 4,752 CH ₄ : 695			
Target reductions: GHG: -1,117 (21%)			
Policy	CO ₂ tax only	CH ₄ tax only	Least-cost CO ₂ tax & CH ₄ tax combination
CO₂ tax level	\$ 48/t	-	\$21/t
CH₄ tax level	-	\$293/t	\$119/t
CO ₂ reductions, MMt (% CO ₂)	1,070 (23%)	798 (17%)	866 (18%)
CH ₄ reductions, MMt CO ₂ eq (% CH ₄)	47 (7%)	320 (46%)	252 (36%)
Average welfare cost per ton reduced	\$180/t	\$126/t	\$112/t
Cost as a proportion of initial income (%)	-1.16%	-0.81%	-0.72%

A CO₂ tax on its own, set at \$48/ton, is required to meet the reduction target. An economy-wide CH₄ tax of \$293/ton meets the reduction target.

The results of the experiment show that a policy with a carbon tax set at \$21/ton along with a methane tax set at a carbon equivalent \$119/ton achieves the reduction target at the lowest welfare cost, lower than either individual GHG policy on its own, and lower than for any other combination of carbon and methane tax levels.

Error! Reference source not found. Figure 6 below shows the full result from the experiment as a welfare cost curve along an emissions isoquant³⁴. The welfare cost of meeting the reduction target (y-axis) is plotted against the CH₄ tax rate on the lower x-axis, with the corresponding CO₂ tax rate on the upper x-axis.

³⁴ An emissions isoquant follows the combinations of CH₄ and CO₂ tax rates that achieve the same level of total emissions reduction.

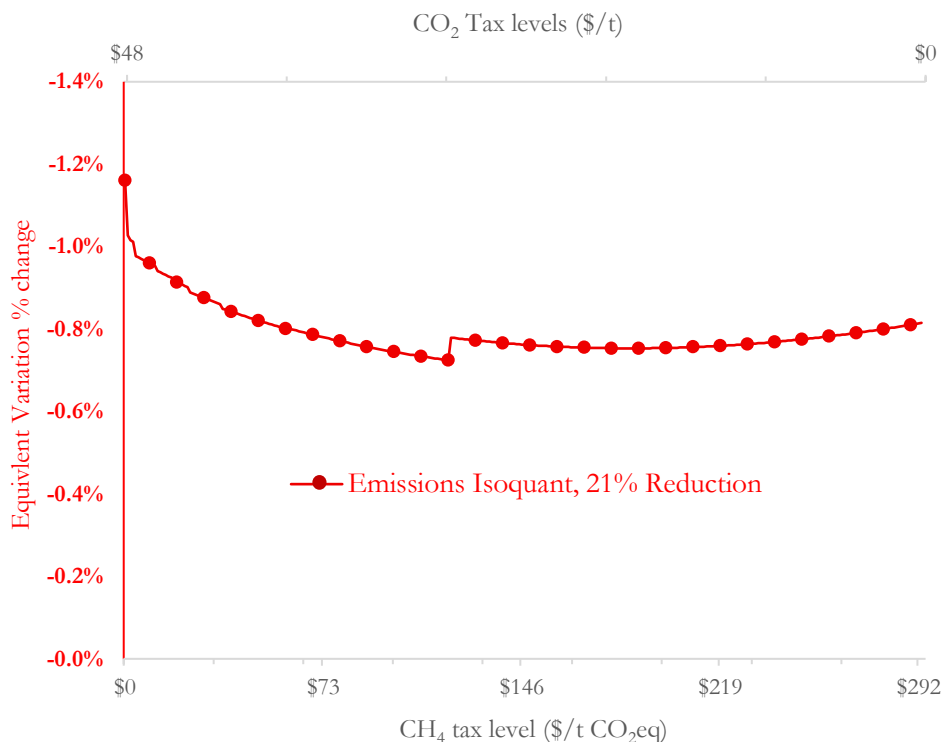


Figure 6: Welfare cost of all combinations of tax levels that achieve the imputed Paris reduction target

At the far left, a CO₂ tax of \$48/t incurs a welfare cost of 1.16% of the representative consumer's real income. As we move right along the x-axis, the CH₄ tax rate increases, the CO₂ tax level decreases and welfare cost reduces to the least-cost point as reported in Table 7 above (0.72%), where the CH₄ tax is \$119/t and the CO₂ tax is \$21/t. The cost then rises again, up to 0.81% of the initial income with the CH₄ tax at \$293/t and no CO₂ tax.

Greenhouse Gas Policy Interactions

Using a combination of policies allows us to achieve the same target reductions at a lower welfare cost because we can take advantage of the maximally cost-effective tranches of emission reductions from each GHG policy, while also accounting for cross-gas policy spillovers and cross-policy interactions. If we are constrained to only using a policy on a single GHG, we cannot take advantage of the relative costs, or the benefits from interactions between policies.

The interactions are complex. Each tax has a different welfare cost for any set level of emission reductions, and a different increasing marginal cost of abatement curve. Each GHG tax generates positive reduction spillovers of the other gas. When both taxes are imposed simultaneously, a cross-policy abatement crowding effect arises: reductions from one policy reduce the marginal effectiveness of the other, primarily because additional abatement occurs higher up the marginal cost curve. In general equilibrium, all these effects take place concurrently. The exact least-cost point is only identifiable in combination, capturing the confluence of different welfare costs, simultaneous bi-directional positive spillover reductions, and policy interactions.

Welfare Cost of Emission Reductions for each Greenhouse Gas Tax

The abatement cost curves in Figure 7 below characterize the welfare cost of each GHG tax as a function of total greenhouse gas reductions, inclusive of the cross-gas spillover abatement. The comparison highlights the differences in cost to achieve a given level of economy-wide emission reductions through a single policy, as well as differences in how marginal costs increase with abatement.

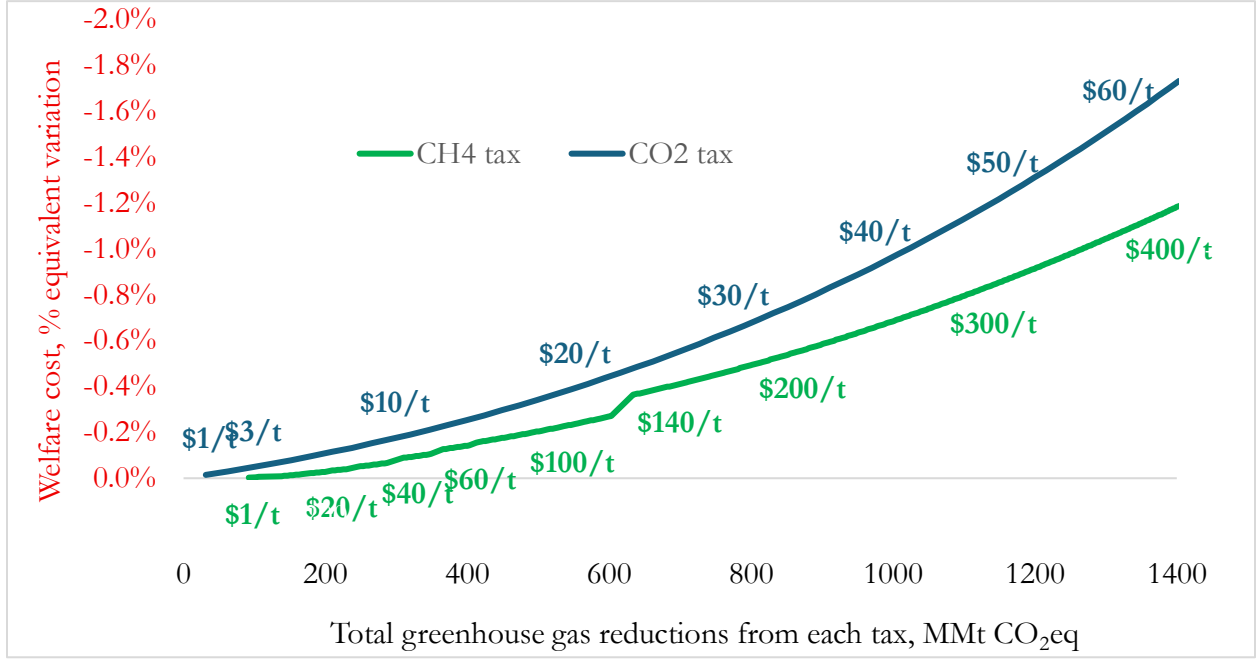


Figure 7: Total welfare cost (percentage change in equivalent variation) of each individual GHG tax as a function of total emission reductions. Labels along each series indicate the tax rate corresponding to the reductions at that point.

Welfare Cost with Cross-Gas Policy Spillovers

Each individual greenhouse gas tax generates positive spillover reduction of the other major greenhouse gas. For each individual GHG policy, the total welfare cost in terms of equivalent variation is the weighted sum of the cost of direct reductions and the cost of the indirect spillover reductions. For the carbon tax (τ_c):

$$EV_{Tot, \tau_{CO_2}} = \frac{EV_{GHG, \tau_c}}{t_{GHG, \tau_c}} \times Q_{GHG, \tau_c} = \frac{EV_{CO_2, \tau_c}}{t_{CO_2, \tau_c}} \times Q_{CO_2, \tau_c} + \frac{EV_{CH_4, \tau_c}}{t_{CH_4, \tau_c}} \times Q_{CH_4, \tau_c} \quad (32)$$

Where EV/t_x is the equivalent variation per ton of a GHG x mitigated, and Q_x is the quantity of that GHG x mitigated with the tax.

The total welfare cost for any level of a carbon tax is the sum of the cost per ton of carbon reductions times the quantity of carbon emission reductions, plus the cost per ton of methane

reductions times the quantity of spillover methane reductions. The marginal costs change with the level of the tax.

The total cost of the methane tax (τ_m) is parallel:

$$EV_{Tot, \tau_{CH_4}} = \frac{EV_{GHG, \tau_m}}{t_{GHG, \tau_m}} \times Q_{GHG, \tau_m} = \frac{EV_{CH_4, \tau_m}}{t_{CH_4, \tau_m}} \times Q_{CH_4, \tau_m} + \frac{EV_{CO_2, \tau_m}}{t_{CO_2, \tau_m}} \times Q_{CO_2, \tau_m} \quad (33)$$

Ultimately, the cost of any combined policy is then the weighted sum of:

- 1) the cost per ton of carbon reductions from the carbon tax times the quantity of carbon emission reductions from the carbon tax, plus
- 2) the cost per ton of methane reductions from the carbon tax times the quantity of spillover methane emission reductions from the carbon tax, plus
- 3) the cost per ton of methane reductions from the methane tax times the quantity of methane emission reductions from the methane tax, plus
- 4) the cost per ton of carbon reductions from the methane tax times the quantity of spillover carbon emission reductions from the methane tax,
- 5) Minus some amount of interaction whereby each policy is less costly because of the effect of the other.

$$EV_{\tau_c, \tau_m, Tot} = \frac{EV_{\tau_c}}{t_{GHG, \tau_c}} \times Q_{GHG, \tau_c} + \frac{EV_{\tau_m}}{t_{GHG, \tau_m}} \times Q_{GHG, \tau_m} - interactions \quad (34)$$

Cross-Policy Abatement Crowding

The cost-effectiveness results show that the interaction term is positive overall, reflecting the net effect of several mechanisms. Within the net effect, cross-policy abatement crowding is unambiguously negative: when both GHG taxes are applied simultaneously, abatement induced by one tax reduces the marginal effectiveness of the other. As abatement under one policy increases, the additional reductions from the second policy diminish.

Figure 8 and Figure 9 below illustrate this diminishing marginal effectiveness across levels of each policy, showing that for a given level of policy stringency, the marginal reductions from each policy are smaller when the other tax is already in place.

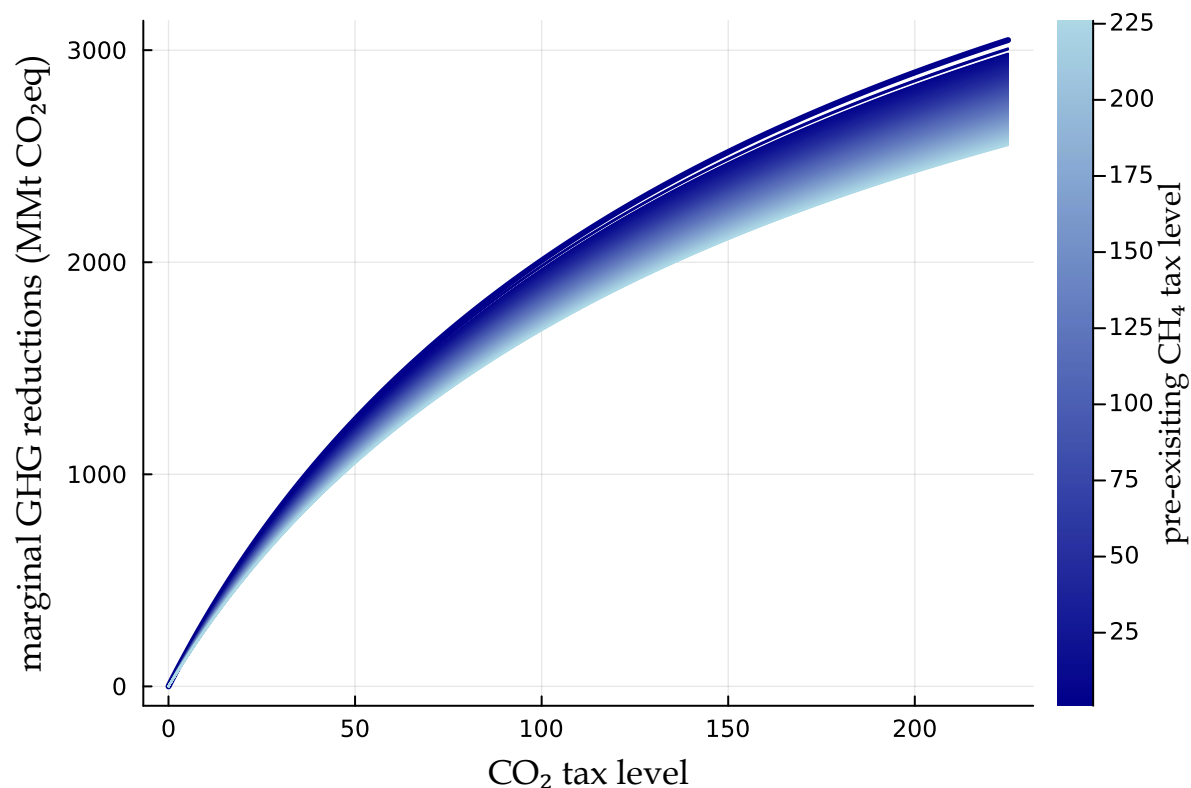


Figure 8: Total GHG emission reductions from increasing levels of CO₂ tax imposed concurrently with CH₄ taxes. Marginal reductions from the CO₂ tax are lower as concurrent CH₄ tax levels increase.

Figure 9 illustrates the marginal impact of the CO₂ tax conditional on CH₄ taxes applied at varying levels. Each point represents the additional GHG reductions achieved by a CO₂ tax, evaluated at a given CH₄ tax level. The 51,000 points plotted result from a combinatorial set of 226 CO₂ tax levels applied across 226 CH₄ tax levels. The figure shows that as the CH₄ tax increases, the marginal reductions from adding a CO₂ tax decline, reflecting the cross-policy abatement crowding effect.

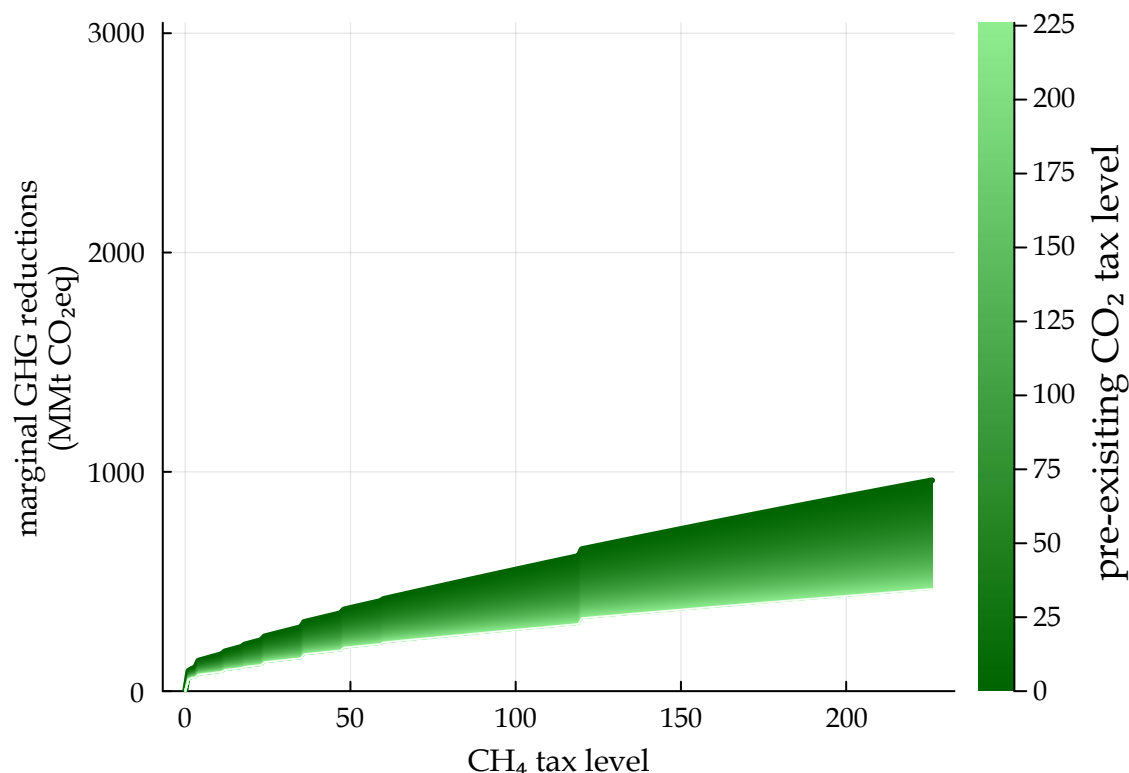


Figure 9: Total GHG emission reductions from increasing levels of CH₄ tax imposed concurrently with CO₂ taxes. Marginal reductions from the CH₄ tax are lower as concurrent CO₂ tax levels increase.

Figure 9 above shows the parallel results for the CH₄ tax, illustrating the marginal impact of the CH₄ tax conditional on CO₂ taxes applied at varying levels. Each point represents the additional GHG reductions achieved by a CH₄ tax, evaluated at a given CO₂ tax level. The figure shows that as the CO₂ tax increases, the marginal reductions from adding a CH₄ tax decline.

4.2.b Least-Cost with methane policy for oil, gas, and pipeline sectors

In the policy scenarios above, I implement an economy-wide carbon tax and an economy-wide methane tax. In an alternative scenario, I run a parallel simulation with the economy-wide carbon tax, but here with methane reduction policy imposed only on the oil, gas, and gas pipeline sectors, representative of the Inflation Reduction Act methane policies.

Table 8 below shows the result from comparing the welfare cost of all combinations of the sector-specific methane tax and an economy-wide carbon. With the methane tax restricted to the oil, gas, and pipeline sectors, a \$406/t CO₂eq tax³⁵ on methane is the least-cost policy that achieves the imputed Paris agreement reduction target³⁶.

³⁵ Multiplied by the CO₂eq factor, that would equal a tax or fee of \$9,828/t CH₄.

³⁶ Total methane emissions in the oil and gas sector in 2022 were less than the GHG reduction target. The CH₄ tax meets the reduction target because it also reduces CO₂ emissions.

Table 8: Tax policy to meet imputed 2022 Paris reduction target, with an economy-wide CO₂ policy and CH₄ policy for just the oil, gas, and pipeline sector

Baseline endogenous emissions (MMt CO ₂ eq) GHG: 5,447 CO ₂ : 4,752 CH ₄ : 695		
Target reductions: GHG: -1,117 (21%)		
Policy	CO ₂ tax only	Least-cost: CH ₄ tax only
CO₂ tax level	\$ 48/t	-
CH₄ tax level	-	\$406/t
CO ₂ reductions, MMt (% CO ₂)	1,070 (23%)	993 (21%)
CH ₄ reductions, MMt CO ₂ eq (% CH ₄)	47 (7%)	124 (18%)
Average cost per ton reduced	\$180/t	\$79/t
Cost as proportion of initial income (%)	-1.16%	-0.51%

Figure 10 below shows the full result from the experiment as a welfare cost curve along an emissions isoquant. The welfare cost of meeting the reduction target (y-axis) is plotted against the CH₄ tax rate on the lower x-axis, with the corresponding CO₂ tax rate on the upper x-axis.

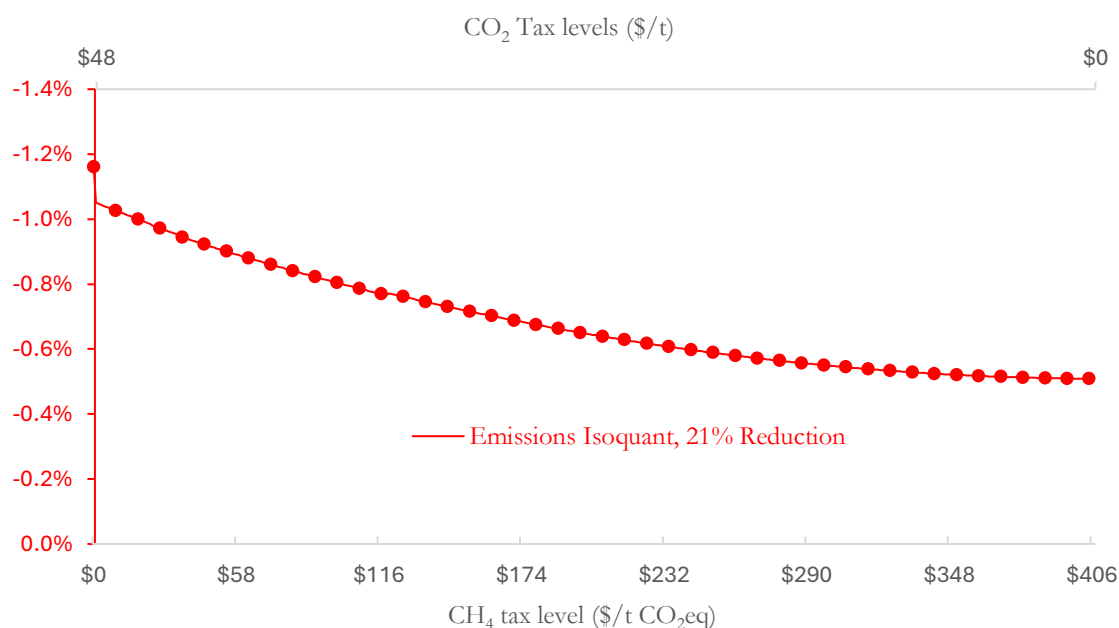


Figure 10: Welfare cost of all combination of CO₂ taxes with CH₄ taxes on the oil, gas, and pipeline sectors that achieve the imputed Paris reduction target.

At the far left, a CO₂ tax of \$48/t has a welfare cost of 1.16% of the representative consumer's real income. Moving right along the isoquant, the sector-specific methane tax increases and welfare cost declines, as abatement is achieved more efficiently. The reduction target is achieved most cost-effectively with a CH₄ tax applied only to the oil, gas, and pipelines sectors.

4.3 Comparison of emission reduction costs

Table 9 below displays the collected results for the scenarios detailed above, highlighting the total GHG reductions and the welfare cost of all policies.

Table 9: GHG emission reductions and welfare cost under the set of policy frameworks for economy-wide taxes on CO₂ and CH₄ and the sector-specific CH₄ tax.

Policy Framework	Policy	CO ₂ tax level	CH ₄ tax level (CO ₂ eq)	Total GHGs reductions, MMt CO ₂ eq (% GHG)	Carbon Reduction (CO ₂ % of total reductions)	Cost as a proportion of initial income (%)	Total cost per ton GHG reduction
Pigouvian first-best	Pigouvian Optimal	\$226/t	\$226/t	3,331 (-61%)	2,973 (89%)	8.86%	\$461/t
Standard Individual Pigouvian Social Cost tax rates	CO ₂ tax (SCCO ₂)	\$226/t	-	2,846 (-52%)	2,719 (96%)	7.89%	\$481/t
	CH ₄ tax (SCCH ₄)	-	\$226/t	939 (-17%)	638 (68%)	0.62%	\$115/t
Extended General Equilibrium Pigouvian	Extended GE Pigouvian CO ₂ tax	\$237/t	-	2,904 (-53%)	2,774 (96%)	8.32%	\$497/t
	Extended GE Pigouvian CH ₄ tax	-	\$706/t	2,037 (-37%)	1,624 (80%)	2.4%	\$205/t
Paris Climate Agreement-aligned reductions	Least-cost CO ₂ tax & CH ₄ tax combination	\$ 21/t	\$119/t	1,117 (-21%)	866 (77%)	0.72%	\$112/t
	CO ₂ tax only	\$ 48/t	-	1,117 (-21%)	1,070 (96%)	1.16%	\$180/t
	CH ₄ tax only	-	\$293/t	1,117 (-21%)	798 (71%)	0.81%	\$126/t
	CH ₄ tax on oil, gas, and pipeline only	-	\$406/t	1,117 (-21%)	993 (89%)	0.51%	\$ 79/t

Imposing both carbon and methane taxes at their first-best Pigouvian social costs produces the largest emissions reductions, in line with the ultimate U.S. 2035 target in the Paris Agreement.

A standard Pigouvian carbon tax alone also induces substantial reductions, but at a higher average welfare cost.

The higher cost of the carbon tax alone, together with the larger share of CO₂ in the abated emissions from the carbon tax, indicates that CO₂ reductions are more costly than CH₄ reductions.

Accounting for the associated methane emissions with the extended general equilibrium Pigouvian tax rate for carbon further increases the welfare cost, reflecting the rising marginal abatement costs of the CO₂ tax.

A standard Pigouvian tax on CH₄ results in much smaller emissions reductions. The lower welfare cost, together with the smaller share of CO₂ in the abated emissions, also reflects that CO₂ reductions are more costly than CH₄ reductions under either policy.

The relative welfare efficiency of the methane tax is further illustrated by comparing the welfare costs across all methane policy scenarios, all carbon policy scenarios, as well as the cost-effectiveness of including a CH₄ tax along with a CO₂ tax under both the full Pigouvian and least-cost reduction target scenarios.

4.4 Alternate Specifications and Sensitivity

Having presented the main results under the central specification, I now test their sensitivity to a set of relevant alternative assumptions. First, I consider a higher estimate of national methane emissions. Next, I examine an alternative parameter value for the global warming potential of methane, emphasizing its stronger near-term warming effect. Finally, I provide an overview of results for combinations of these alternative assumptions.

4.4.a Shorter Term Global Warming Potential Parameter for Methane CO₂ Equivalence

To compare methane emissions alongside CO₂ the methane data in this analysis uses the standard CO₂ equivalent (CO₂eq) unit for methane emissions. CO₂ equivalence adjusts from the mass measure of CH₄ emissions, to report the amount that would contribute equivalently to global warming relative to CO₂. Methane has a much stronger effect on radiative forcing than CO₂ but decays in the atmosphere more quickly. CO₂eq embeds a choice of comparison period for methane's Global Warming Potential (GWP) relative to CO₂. In my central specification, I default to the common 100-year period³⁷ from the original base data³⁸. In light of the potential for methane

³⁷ <https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review/methods-for-climate-change-transparency/common-metrics>

³⁸ A 100-year GWP considers methane's impact on global warming over a 100-year period relative to carbon dioxide of equal mass over the same time frame.

mitigation to be impactful in limiting nearer term peak temperature³⁹, I also test a 20-year GWP of 81.2⁴⁰ as an alternative specification.

With the relative impact of methane measured in this way, methane becomes a much greater share of emissions, and the assessment of total emissions is higher. Measured in this way, methane emissions represent a much larger contribution to GHGs in the U.S., 32% of greenhouse gases for 2022⁴¹ compared to 11% when assessed in terms of the 100-year GWP. I also adjust the imputed Paris Agreement-aligned target accordingly. Table 10 below reports the result from my policy simulation with the methane emissions adjusted to account for the alternative GWP value.

Table 10: Tax policy to meet imputed 2022 Paris reduction target, modelled in the context of nearer term warming potential for methane

Scenario: 20-year GWP = 81.2 CO ₂ eq			
Baseline endogenous emissions (MMt CO ₂ eq) GHG: 7,010 CO ₂ : 4,752 CH ₄ : 2,258			
Target reductions: GHG: -1,404 (20%)			
Policy	CO ₂ tax only	CH ₄ tax only	Least-cost CO ₂ tax & CH ₄ tax combination
CO₂ tax level	\$58/t	-	\$ 5/t
CH₄ tax level	-	\$55/t	\$47/t
CO ₂ reductions, MMt (% CO ₂)	1228 (26%)	552 (12%)	615 (13%)
CH ₄ reductions, MMt CO ₂ eq (% CH ₄)	1178 (8%)	851 (38%)	789 (35%)
Total reduction cost per ton	\$182/t	\$68/t	\$64/t
Cost as a proportion of initial income (%)	-1.47%	-0.55%	-0.52

A higher carbon tax rate is needed to achieve the adjusted reduction target, relative to the central, 100-year GWP specification. In contrast, methane policy achieves the adjusted target reductions with substantially lower stringency, represented by a methane tax of \$55/t. This reflects the increased importance of methane emissions alongside the effectiveness of the CH₄ tax in targeting them. Furthermore, direct abatement covers a higher level of emission reductions, requiring lower levels of CO₂ spillover reductions to meet the target.

Results of an experiment evaluating the welfare costs of policy combinations show that a carbon tax set at \$5/t combined with a methane tax set at \$47/t achieves the reduction target at the lowest welfare cost. This combination has a lower welfare cost than either single-instrument GHG policy or any other combination of carbon and methane tax levels.

³⁹ The Paris agreement set a goal of keeping global average temperature below 2°C - and as close as possible to 1.5°C - above pre-industrial levels. Current estimates for 2024 are 1.28°C.

⁴⁰ The central estimate under a 20-year period GWP from the 6th IPCC Assessment Report.

⁴¹ This estimate does not include parallel GWP updates for other non-CO₂ GHGs (not included in this model).

These results suggest that placing greater weight on the climate impact of methane as a greenhouse gas reinforces the policy relevance of the relative welfare efficiency of CH₄ reductions.

4.4.b Higher Methane Emission Estimates

The methane emission data used for the analysis above aligns with the 2024 EPA greenhouse gas inventory, but recent research suggests that methane emissions could be much higher than the official estimates from the US EPA Greenhouse Gas Inventory. (Alvarez et al. 2018) find that methane leaks in the oil and gas supply were 60% higher than official estimates because of missed assessments of abnormal operations. (Plant et al. 2022) look at flaring in the fossil fuel industry and find that unlit flares and inefficient combustions lead to methane emissions from the oil and gas sector that are 5 times official estimates. I incorporate that research and increase methane emissions from the oil and gas sector to 500% of the EPA values in my model. In Table 11 below I report my results using these adjusted emissions, abatement potential, and the reduction target.

Table 11: Tax policy to meet imputed 2022 Paris reduction target, modelled in the context of higher CH₄ emissions estimate.

Scenario: 500% Oil and gas CH ₄ emissions		
Baseline endogenous emissions (MMt CO ₂ eq)	GHG: 6,362	CO ₂ : 4,752 CH ₄ : 1,610
Target reductions:	GHG: -1,285 (20%)	
Policy	CO ₂ tax only	CH ₄ tax only
CO₂ tax level	\$50/t	-
CH₄ tax level	-	\$44/t
CO ₂ reductions, MMt(% CO ₂)	1097 (23%)	646 (14%)
CH ₄ reductions, MMt CO ₂ eq (% CH ₄)	188 (12%)	639 (40%)
Total reduction cost per ton	\$163/t	\$47/t
Cost as a proportion of initial income (%)	-1.21%	-0.35%

In parallel with the 20-year GWP assumption, methane accounts for a larger share (25%) of overall emissions in this scenario, and total measured emissions are correspondingly higher. As a result, a slightly higher carbon tax is needed to achieve the adjusted reduction target, while a lower level of methane policy stringency is sufficient. Under this assumption, a methane policy on its own achieves the reduction target at the lowest welfare cost.

4.4.c Higher Methane Emission Estimates and Shorter-Term Temperature Impact from Methane

In Table 12 below, I report the results from my policy simulation using both the higher estimate of methane from the oil and gas sectors and the nearer-term 20-year GWP value for the CO₂eq unit conversion in combination.

Table 12: Tax policy to meet imputed 2022 Paris reduction target, modelled in the context of higher CH₄ emissions estimate, and in combination with nearer term warming potential.

Scenario: 500% Oil and gas emissions & GWP = 81.2		
Baseline endogenous emissions (MMt CO ₂ eq)	GHG: 9,981	CO ₂ : 4,752 CH ₄ : 4,751
Target reductions:	GHG: -1,948 (20%)	
Policy	CO ₂ tax only	CH ₄ tax only
CO₂ tax level	\$59/t	-
CH₄ tax level	-	\$7/t
CO ₂ reductions, MMt (% CO ₂)	1246 (26%)	460 (8%)
CH ₄ reductions, MMt CO ₂ eq (% CH ₄)	702 (13%)	1588 (30%)
Total reduction cost per ton	\$134/t	\$14/t
Cost as a proportion of initial income (%)	-1.5%	-0.15%

With both of these assumptions, methane is a much greater proportion of emissions. In this simulation, reducing methane is even more impactful, resulting in a much lower CH₄ tax rate required, and a lower welfare cost to achieve the adjusted reduction target.

4.4.d Optimal Policy Under Alternative Specifications

In Table 13 below I report the most cost-effective policies for the alternative specifications with both policy scenarios in combination. I vary the GWP assumption for methane relative to CO₂, and assume oil and gas sector methane emissions are 5 times the EPA greenhouse gas inventory values. I do this for economy-wide taxes on both GHGs, and for the scenario with the CH₄ tax imposed only on the gas, oil, and pipeline sectors. In the first row, I report the results for my central specification as a reference. Looked at together, we see that in settings where methane is more significant relative to carbon emissions, the CH₄ policy stringency necessary to meet the reduction target is lower, the least-cost policy shifts toward the methane tax, and in general the welfare cost is lower.

Table 13: Optimal policy for the Paris agreement target given alternative assumptions

Scenario			Emissions	CH ₄ % of Total Emissions	CO ₂ tax	CH ₄ tax	Revenue	Welfare Cost
GWP	oil gas CH ₄	CH ₄ tax						
100-year	100%	econ-wide	5,447	13%	\$21/t	\$119/t	144 B\$US	-0.72%
100-year	500%	econ-wide	6,362	25%	-	\$44	42 B\$US	-0.35%
20-year	100%	econ-wide	7,010	32%	\$5 /t	\$47	92 B\$US	-0.52%
20-year	500%	econ-wide	9,981	52%	-	\$7	24 B\$US	-0.15%
100-year	100%	oil/gas/pipe	5,447	13%	-	\$393	37 B\$US	-0.11%
100-year	500%	oil/gas/pipe	6,362	25%	\$2/t	47	38 B\$US	-0.37%
20-year	100%	oil/gas/pipe	7,010	32%	\$1/t	\$119	42 B\$US	-0.54%
20-year	500%	oil/gas/pipe	9,981	52%	-	\$9	20 B\$US	-0.19%

Conclusion

This paper highlights the importance of interactions between greenhouse gas mitigation policy, economic activities, and emissions of carbon dioxide and methane, with several key policy implications.

First, in any policy setting short of first-best Pigouvian taxation of both gases, an externality tax applied to a single greenhouse gas should account for the combined climate externality from both co-produced emissions, rather than the damages from the targeted gas alone. I showed that the economic and emissions link between methane and carbon dioxide implies that the socially efficient externality tax rate should account for this co-production. I refer to this as an extended general equilibrium Pigouvian rate. The implications should be valid for any policy setting in which either gas is not taxed at the first-best Pigouvian rate. This insight also applies to other cases where multiple pollutants connected through economic activity generate the same externality. I estimated the magnitude of co-production for the U.S. in 2022 and determined that an extended GE Pigouvian tax on methane should be over 200% higher than the social cost of methane, while an extended GE Pigouvian tax on carbon should be about 5% higher than the social cost of carbon.

Second, implementing CO₂ and CH₄ policies jointly can substantially reduce the welfare cost of mitigation by taking advantage of the distinct benefits of each policy in combination. I evaluated the welfare cost of CO₂ policy, CH₄ policy, and combined policy under a common reduction target. For the central specification, the policy experiment reveals that a methane tax of \$119/t⁴² CO₂eq along with a CO₂ tax of \$21/t achieves Paris Agreement-aligned reductions at the lowest welfare cost. I examined the mechanisms underlying this result to illustrate the channels of this welfare efficiency in general equilibrium. The results indicate that methane mitigation is less costly than CO₂ policy, but combined policies still are least costly. For settings and assumptions that weigh methane relatively higher against carbon, methane policy becomes increasingly impactful, with lower relative welfare costs. I use taxes to tractably represent emissions reduction policies, but these conclusions should be broadly applicable for other types of climate policy. Taken together, these results highlight the importance of coordinated, multi-gas policy design for cost-effective climate mitigation.

Third, evaluations of the effectiveness, or potential effectiveness, of a policy targeting either GHG must account for cross-gas policy impacts. I showed that policy targeting either of the major greenhouse gases will also affect the other because of the economic and emissions link between them. I characterized the central mechanisms of these cross-gas policy effects that include both positive and negative cross-gas drivers. Using a numerical general equilibrium model of the United States, I found that the net effects are complementary. My analysis highlights the potential significance of cross-policy interactions and underscores the importance of joint analysis.

Finally, my results indicate that the Paris Agreement target falls short relative to the socially optimal level of emissions reductions implied by first-best Pigouvian taxes on both gases.

⁴² 53% of the social cost of methane estimate used in this study.

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