Optimal Allocation of Abatement Effort under Political Constraints: The Economic Cost of Delaying Sectoral and Economy-wide Climate Policies

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Abstract

Despite commitments to address climate change, governments face political challenges to implementing first-best policies. These challenges cause policymakers to delay climate action, especially in politically sensitive sectors of the economy. Taking political headwinds as an exogenous constraint, this paper analyzes the cost of delaying climate policies both at a sectoral level and economy-wide. The paper demonstrates that delaying climate action is more expensive than distorting the allocation of effort across sectors. More precisely, it is more expensive to delay economy-wide climate policies than to delay action only in a subset of sensitive sectors, which is, in turn, more expensive than immediately implementing a less ambitious policy (*e.g.*, a lower-than-optimal carbon price) in sensitive sectors. The paper then uses numerical simulations to show that sectoral emissions rates, rather than abatement costs, drive the cost of delaying climate action in a given sector. This is because delaying action in sectors with high emissions rates causes a large distortion in the allocation of effort across the rest of the economy, which increases costs. Failing to capture low cost abatement opportunities does increase policy costs (because it requires doing more in expensive sectors) but this effect is smaller than delaying high emissions sectors. Finally, the paper shows that, in practice, climate action is most expensive to delay in the energy sector, because it possesses both a high emissions rate and a low marginal investment cost. The paper can provide guidance for policymakers navigating the political-economic landscape while still aiming to achieve climate goals.

JEL: P18; Q52; Q54; Q58
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1 Introduction

Upon signing the Paris Agreement in 2015, a multitude of nations committed to pursuing policies that would limit global warming to "well-below" 2 °C and to put significant effort towards limiting warming to 1.5 °C (United Nations Framework Convention on Climate Change, 2015). While challenges to decarbonization abound, political economy constraints are of particular consequence to meeting the

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Paris Agreement targets. Such political constraints are broadly defined as political headwinds – such as thin majorities in legislative bodies, disapproving voter blocs, inhibiting government bureaucracy, or powerful lobby groups with *de facto* veto power – that prevent policymakers from implementing the most efficient policies to address a particular challenge (Jenkins, 2014). For instance, policymakers often struggle to implement policies to promote decarbonizing the passenger transport sector (because of opposition to higher gasoline prices) or the agricultural sector. Countries with oil and gas reserves also have energy subsidies that are difficult to reform; for example, while the Group of Twenty and the Asia-Pacific Economic Cooperation committed to phasing out inefficient energy subsidies in 2009, many nations still heavily subsidize fossil fuel use (Asian Development Bank, 2015; Black et al., 2023; Damania et al., 2023; Ihsan et al., 2024). Political economy constraints can also change in response to policy: for example, proponents of carbon pricing often support near-term subsidy-based green industrial policies to build political coalitions to support carbon prices down the line (Wagner et al., 2015; Meckling et al., 2017).

Current evidence suggests that political opposition to climate policies in certain sectors or regions leads either to a delay in climate action (when opposition is strong enough to build a coalition against any climate policy) or to heterogeneous (and sub-optimal) policy approaches that mobilize isolated sectoral policies, subsidies-based policies, or command-and-control regulations (Dolphin et al., 2019; World Bank, 2023; Hallegatte et al., 2023; Stechemesser et al., 2024). Even economy-wide policies have a number of exceptions; for example, they may only cover a share of total emissions (as is the case for European ETS), have a number of exemptions (*e.g.*, on air transport fuels), or apply different prices to different CO_2-emitting fuels (such as higher tax levels on liquid fuels compared to coal) (World Bank, 2024). One practical example is the bifurcated European Union emissions trading systems (ETSs), which impose different carbon prices on different sectors of the economy and contain a number of exemptions (European Commission, 2005, 2023; World Bank, 2024). Each of these examples illustrate how policymakers are managing the idiosyncrasies of the green transition in their countries while navigating differences in abatement costs, sectoral characteristics, and, especially, political challenges.

This paper explores how delaying climate policies in order to accommodate political constraints, both at a sectoral level and economy-wide, increases the cost of the green transition.[1] To this end, we build on the multi-sector investment model presented by Vogt-Schilb et al. (2018) and allow the policymaker to wield two climate policy instruments: (1) a carbon price/ETS (that can be either homogeneous or heterogeneous across economic sectors), and (2) the targeted delay of climate policies in either a set of sectors or economy-wide. Our multi-sector approach allows the planner to delay policies impacting only a subset of economic sectors, differing from past work which either takes a global view (Lecocq et al., 1998; Sanderson and O'Neill, 2020) or focuses on individual regions as opposed to sectors within those regions (Andaloussi et al., 2022). We then elucidate the impact of sub-optimal policies on decarbonization investment schedules, carbon prices, the temporal distribution of investment in abatement technologies, and the aggregate economic cost of delay.

Importantly, our model includes the effects of adjustment costs (Lucas, 1967) on the green transition. Adjustment costs capture the convex relationship between the cost of investment in abatement capital stocks – here treated as technologies that, over their capital lifetimes, reduce greenhouse gas emissions – and the rate that capital is installed (Mussa, 1977). The sources of adjustment costs are widespread, including supply constraints, labor training and re-training costs, and the opportunity cost of using scarce resources. Recent work has argued that adjustment costs lead to more up-front investments in clean technologies by increasing the optimal carbon price (for example, Campiglio et al. (2022) suggest a roughly 30% premium relative to a model without adjustment costs). Such effects are important to

[1] Note that we do not attempt to model political constraints directly. Rather we treat them as exogenous constraints and explore how these constraints impact the optimal timing and distribution of investments in clean technologies. See Besley and Persson (2023) and Kalk and Sorger (2023) for theoretical treatments of the political economy of decarbonization, Ulph and Ulph (2013) for a model of optimal policies when governments cannot commit to long-term climate policies because of political constraints, and Hallegatte et al. (2023) for a discussion about how political constraints can be overcome in practice.

consider when analyzing the economic consequences of delaying decarbonization: if a policymaker is intent on reaching net-zero by some future date, any delay in starting policy will shrink the horizon over which the transition can occur, thus increasing the rate of decarbonization and incurring adjustment costs.

Our first contribution is to develop three scenarios where the policymaker manages political constraints by relaxing or delaying climate policies impacting politically vocal sectors; throughout, we use "vocal" to signify the sectors that are vocal opponents of climate policies, for one reason or another.

The first option is to immediately implement a heterogeneous carbon price regime, wherein the policymaker reduces the carbon price facing the politically vocal sectors, thereby giving them more time to decarbonize. This approach is common in a number of nations with existing carbon prices that also face political challenges (Dolphin et al., 2019). Throughout, we will refer to this approach – to immediately implement a below-optimal carbon price in politically vocal sectors to accommodate political constraints – as "relaxing" climate policies in vocal sectors.

Another choice is a delayed, sectorally heterogeneous approach. In this policy suite, the policymaker delays *all* climate policies impacting the set of vocal sectors, therefore giving the sectors more time to plan emissions reductions.

Finally, the policymaker can implement a delayed, homogeneous policy suite. In this policy, the policymaker delays *all* climate policies *economy-wide* while they wait for political changes that would make the theoretically efficient policy palatable (*e.g.*, if proponents of climate policy can build coalitions to enable action in all sectors during the delay period).

We use our model to quantify the cost difference between each of these three policy options relative to the optimal policy: we estimate that the marginal cost of delaying climate policies economy wide can exceed $2.5 trillion per year of delay, while the marginal cost of relaxing or delaying policies in a single politically vocal sector are at most $76 billion or $397 billion per year, respectively. A first conclusion is that it is less costly to be flexible and reduce ambition in vocal sectors – and thus deviate from the optimal allocation of emission reduction across sectors – rather than delaying action in all sectors.

Our second contribution is then to ask: if political constraints lead a policymaker to relax or delay climate policies in a set of vocal sectors, what sectoral characteristics would lead to the largest increase in cost? To address this question, we carry out two sets of numerical experiments.

The first is a large grid of simulations where we simulate a two-sector economy with varying combinations of sectoral characteristics. In particular, we analyze how different sectoral configurations of marginal abatement investment costs, emissions rates, and capital depreciation rates impact total policy costs when investments in abatement capital stocks in one sector are delayed.

These experiments yield two findings. One is that delaying sectors with high emissions rates leads to the largest increase in policy costs. Delaying action in high emissions sectors requires large amounts of emissions to be reallocated to accommodate the delay. This strongly distorts the allocation of abatement investments by driving up the carbon price facing the rest of the economy. The higher carbon price, in turn, leads to an accelerated decarbonization of the remaining, non-vocal sectors, which is expensive because of adjustment costs.

The second finding is that, normalizing by sectoral emissions rates, delaying low-cost abatement opportunities[2] is more expensive than delaying high-cost abatement opportunities. This finding is somewhat natural: putting off investments in "low hanging fruit" leads to more expensive investments being made sooner-than-optimal, which increases the cost of decarbonization. However, we find this effect to be dwarfed by the effect of reallocating emissions mentioned earlier by about a factor of two. Therefore, our results suggest that the usual framing – in which the cost of a sub-optimal distribution of effort across sectors is driven by inter-sector differences in marginal abatement costs (Baranzini et al., 2017; Stiglitz, 2019; Gugler et al., 2021) – may have overlooked the joint role of adjustment costs and

[2]Low-cost abatement opportunities are investments with low total abatement value; as we will make concrete in Sections 2 and 4, these are investments in sectors with low marginal investment costs or low capital depreciation rates.

sectoral emissions intensities that lead to larger increases in the cost of a sub-optimal allocation of efforts across the economy.

The final insight from our analysis comes from our second set of numerical experiments, where we calibrate our model to Intergovernmental Panel on Climate Change (IPCC) data for marginal costs, emissions rates, and carbon budgets. We find that the energy sector is the most expensive sector to delay climate action in. This can be explained by energy having both a high emissions rate *and* a low marginal abatement cost. Therefore, energy almost perfectly characterizes a sector that is expensive to delay given the effects discussed above. We further find that, in practice, the sectoral emissions intensity is the dominant factor of the cost of delaying climate action in a given sector. These insights provide a "rule of thumb" for policymakers, which is that it is cheap to delay action in sectors with small emissions (and vice versa), with the cost of abatement technologies in the sector likely playing a secondary role.

Our analysis proceeds as follows. We outline the general theoretical model in Section 2. Our different policy scenarios are outlined and linked to model parameters in Section 3. We then carry out two sets of numerical simulations to demonstrate model behavior in Section 4: a simplified two-sector model and a two-sector sensitivity test. Section 5 presents another set of numerical simulations, this time calibrated to IPCC data for sectoral marginal investment costs, emissions intensities, and carbon budgets. We summarize our findings, discuss policy implications of our work, present a few caveats to our approach, and posit directions for future study in Section 6.

2 Model

2.1 Forerunners

The model considers an economy with a set of sectors given by I. Each sector $i \in I$ can be characterized by four parameters: the emissions intensity, $\bar{a}_i$, the capital depreciation rate, δ_i, the marginal investment cost of abatement capital, $\bar{c}_i$, and the start time, $t_{0,i}$, before which no abatement investment occurs in the sector. The model represents a centralized planner that decarbonizes the economy for the least cost such that some emissions budget, B – referred to as the remaining carbon budget, or just "the carbon budget" – is not exceeded. Here, the carbon budget is a geophysical quantity that relates the amount of carbon dioxide emissions the atmosphere can withstand before a particular long-term temperature threshold is crossed (Intergovernmental Panel on Climate Change, 2021). While we treat the carbon budget as a global quantity, the carbon budget can also be interpreted as the integrated flow of emissions a particular nation has committed to in compliance with their nationally determined commitment (or NDC). Our model would then inform the cost of being compliant with the NDC.

To limit greenhouse gas emissions, the planner must invest in abatement *capital stocks*; this is a departure from other integrated assessment models that allow the planner to tune the *abatement rate* directly (such as Nordhaus, 2017). Past work suggests that integrated assessment models where the social planner chooses the abatement rate directly can lead to unsound policy advice (Vogt-Schilb and Hallegatte, 2014). We treat abatement capital stocks as abatement technologies that, once invested in, reduce greenhouse gas emissions over their capital lifetimes. This implies that abatement is embodied in these capital stocks, following the "committed emissions" framework originally developed by Davis and Socolow (2014). As an example, if one builds a green cement plant with a capital lifetime of 40 years which replaces a dirty cement plant that emitted 0.5 $MtCO_2$ per year, then building a green cement plant represents an investment in abatement equal to 0.5 $MtCO_2$ per year, as long as the clean plant is in operation. The social planner must therefore build up abatement capital stocks over the investment horizon (while also replacing capital as it depreciates) such that the economy's greenhouse gas emissions rate reaches zero when the carbon budget is depleted.

With this background, we write investment and abatement in a given sector $i \in I$ as $x_i(t) > 0$ and $a_i(t) > 0$, respectively, and the economy-wide cumulative emissions as $\psi(t)$. The planner discounts the future at a rate r. The cost of a unit of investment in the sector $i \in I$ is given by $c_i(x_i(t))$, which is assumed to be an increasing and convex function of investment.

The convexity of our cost function captures the impact of adjustment costs on the green transition (Lucas, 1967; Mussa, 1977). Adjustment costs capture the propensity for a fast transition away from fossil fuels to be more expensive than a slow transition. For example, if one wants to retrofit a fleet of buildings to be energy efficient and carbon-free, doing so quickly would require training new builders and electricians, as well as pre-maturely consuming productive resources that could be more productively used elsewhere in the economy, compared to a slower transition. The cost of training additional workers to accommodate labor shortages, as well as the opportunity cost of using scarce materials for decarbonization as opposed to other economic activity, are examples of "adjustment costs". These effects lead the marginal cost of abatement capital, $c'(x)$, to be an increasing function of the rate of capital installed, x, therefore making $c(x)$ convex.

2.2 The Optimal Policy

In this setup, the first-best policy[3] is the strategy where the planner immediately begins investing in each economic sector, implying that for all $i \in I$, $t_{0,i} = 0$. The planner then solves,

$$\begin{aligned} \min_{\{x_i(t)\}_{i \in I}} & \int_0^\infty e^{-r\zeta} \sum_{i \in I} c_i(x_i(\zeta)) d\zeta, \qquad (2.1) \\ \text{Subject to : } & \dot{a}_i(t) = x_i(t) - \delta_i a_i(t), \\ & \dot{\psi}(t) = \sum_{i \in I} (\bar{a}_i - a_i(t)), \\ & 0 \leq a_i(t) \leq \bar{a}_i, \\ & 0 \leq \psi(t) \leq B. \end{aligned}$$

This model was studied extensively in Vogt-Schilb et al. (2018). Using the optimal path of abatement, $a_i^*(t)$, we can determine the *ex ante* optimal allocation of emissions to a sector $i \in I$ as

$$B_i^* := \int_0^\infty (\bar{a}_i - a_i^*(\zeta)) \, d\zeta, \qquad (2.2)$$

which will be important for our discussion later.

For the purposes of our paper, two theoretical insights about this model are relevant. The first is that the model exhibits a steady-state solution, where cumulative emissions and abatement in each sector is held constant at their upper bounds, $\psi(t) = B$ and $a_i(t) = \bar{a}_i$ for each $i \in I$; this implies that $x_i(t) = \delta_i \bar{a}_i$ in the steady state. The steady state investment cost, $c_i(\delta_i \bar{a}_i)$, quantifies the total value of abatement capital in the sector.

The point in time where the abatement equals the emissions rate (and therefore there is no residual emissions in the sector) can be referred to as the "decarbonization date" of that sector, which we denote as T_i^*. The decarbonization date is determined endogenously and is linked to the carbon price that faces the sector(s), as higher carbon prices lead to more investment and therefore sooner decarbonization dates (and vice versa). As we will later discuss, a possible way to accommodate a political constraint is to lower the optimal carbon price facing a set of vocal sectors, which, in effect, pushes the decarbonization date of vocal sectors further into the future.[4]

[3] Throughout, we refer to the solution of (2.1) as the "optimal" or "first-best" policy; every other policy we analyze is referred to as "sub-optimal" or "second-best". For our purposes, the solution to (2.1) represents both a qualitative and quantitative benchmark against which we can measure the qualitative and quantitative implications of various sub-optimal policies later.

[4] This could be an implicit goal in the European Union's ETS2. ETS2 follows different rules and has a lower starting

The second relevant theoretical insight is that the optimal investment pathway of (2.1) takes two general forms: a declining path or a bell-shaped path (see Proposition 1 from Vogt-Schilb et al. (2018)). The intuition for this result can be gleaned from the optimal path of marginal investment costs of (2.1) (see Eqn. (10) in Vogt-Schilb et al. (2018) or Eqn. (A.8)), which can be written as

$$\frac{dc_i'(x_{i,t})}{dt} = (r + \delta_i)c_i'(x_{i,t}) - \mu e^{rt} \tag{2.3}$$

where μ is the carbon price, determined endogenously as the shadow value of emissions reductions. From (2.3), one can see that if the marginal implicit rental cost of capital[5] (given by $(r + \delta_i)c_i'(x_{i,t})$) is greater than the carbon price (given by μe^{rt}), it is optimal to increase investments over time before declining to the steady state. On the other hand, if the carbon price is larger than the marginal implicit rental cost, the optimal choice is to invest in capital up-front, which leads to a declining investment pathway. As we will see later, the imposition of political constraints on the optimal policy will alter the carbon price facing either the entire economy or some subset of economic sectors, thereby tilting the balances either towards or away from abatement investments in the near-term.

2.3 Incorporating Political Economy Constraints

To incorporate political constraints, of the set of economic sectors I, we denote some subset, $V \subset I$, as being politically vocal, while the remaining sectors, $N := I \setminus V$, are not (comparatively) politically vocal. The planner accommodates the political constraint by splitting the optimal policy described by (2.1), in which all sectors face a unique and perfectly-credible emissions cap/carbon price, into two separate, independent schemes. They then allocate a premium amount of emissions, $B_p > 0$, to the politically vocal sectors to the detriment of the non-vocal sectors. This procedure poses each set of sectors with their own carbon price, $\mu_j(t)$, and emissions cap B_j. Each group of sectors' stock of CO_2 emissions are tracked separately as $\psi_j(t)$ for each $j \in \{V, N\}$.

It is worth mentioning that throughout, we consider a planner that always meets the constraint that emissions are kept below B. In reality, it may be possible that political constraints force the planner to simply adopt a higher carbon budget, or at a national level, for the policymaker to weaken its NDC. Policymakers may also wait to implement decarbonization policies until the cost of abatement technologies decline owing to global knowledge spillovers from countries with climate policies, i.e., they are "free riders" (Nordhaus, 2021). This, of course, will come at a price, whether that be in terms of increased climate damages or reputational costs for failing to achieve commitments made to the international community. Our analysis is not focused on these factors, as the question of increased damages and risk from delaying climate policies has been well-explored (for example, as in Daniel et al. (2019), Sanderson and O'Neill (2020), and Bauer et al. (2024b)). Rather, we are focused on the transition cost – that is, the cost of completing the required investments in abatement capital stocks to decarbonize one's economy – associated with political constraints that prevent the first-best investment strategy from being pursued (along similar lines as The Council of Economic Advisors to the White House (2014) and Andaloussi et al. (2022)).

Given the above discussion, we can formulate the optimal control problem for the politically con-

price than ETS1, implying that the covered sectors (*e.g.*, transportation) will be decarbonized later than if they were incorporated into ETS1, where carbon prices are often over 80€/tCO_2 (European Commission, 2023).

[5] The marginal implicit rental cost of capital is the rental price at which an optimal planner would be indifferent between renting capital or buying capacity at $c_i'(x)$, as first proposed by Jorgenson (1967).

Table 1. Policy Suites and How They Influence Model Parameterization. μ_V and μ_N are the carbon prices applied to the politically vocal and non-vocal sectors, respectively; $t_{0,V}$ and $t_{0,N}$ are the start times of the policies for the vocal and non-vocal sectors, respectively; and T_V and T_N are the decarbonization dates of politically vocal and non-vocal sectors, respectively. B_p is the emissions premium. Throughout, δT represents the amount of time that a policy is delayed. We use exact representations of parameters when possible. When exact expressions cannot be written (because some values, like decarbonization dates, are determined endogenously), we use arrows to represent if the quantity is larger or smaller than the optimal and by how much. An entry of "opt" indicates that optimal value for the policy suite is the same as the first-best.

Policy suite	μ_V	$t_{0,V}$	T_V	μ_N	$t_{0,N}$	T_C	B_p
First-best	opt	0	opt	opt	0	opt	0
Immediate Heterogeneous Policy	$\downarrow$	0	$T_V^* + \delta T$	$\uparrow$	0	$\downarrow$	Varies, see App. C
Delayed Heterogeneous Policy	opt	δT	$T_V^* + \delta T$	$\uparrow\uparrow$	0	$\downarrow\downarrow$	$\sum_{i \in V} \bar{a}_i \delta T$
Delayed Economy-wide Policy	$\uparrow\uparrow\uparrow$	δT	$\downarrow\downarrow\downarrow$	$\uparrow\uparrow\uparrow$	δT	$\downarrow\downarrow\downarrow$	$\sum_{i \in I} \bar{a}_i \delta T$

strained policymaker as,

$$\begin{aligned}
&\min_{\{x_i(t)\}_{i\in I}} \sum_{i \in I} \left[\int_{t_{0,i}}^{\infty} e^{-r\zeta} c_i(x_i(\zeta)) d\zeta \right], \qquad (2.4)\\
&\text{Subject to}: \dot{a}_i(t) = x_i(t) - \delta_i a_i(t), \qquad i \in I,\\
&\qquad \dot{\psi}_j(t) = \sum_{k \in j} \left(\bar{a}_k - a_k(t)\right), \qquad j \in \{V, N\},\\
&\qquad 0 \leq a_i(t) \leq \bar{a}_i, \qquad i \in I,\\
&\qquad 0 \leq \psi_j(t) \leq \sigma_j B_p + \sum_{k \in j} \left(B_k^* - t_{0,k}\bar{a}_k\right), \qquad j \in \{V, N\},\\
&\qquad \sigma_j = \begin{cases} 1 & \text{if } j \in V \\ -1 & \text{if } j \in N \end{cases}.
\end{aligned}$$

We derive the analytic solution to (2.4) in Appendix A.

3 Policy Suites

3.1 Narratives

Policymakers can relax or delay decarbonization initiatives in a set of economic sectors, or across the entire economy, to accommodate political constraints. These approaches generally take two forms, as either homogeneous or heterogeneous policies across sectors. A homogeneous policy faces each economic sector with the same, harmonized, perfectly-credible carbon price; to address political concerns, the policymaker could delay the onset of this carbon price schedule. One way of viewing this approach is that the policymaker is sacrificing the efficient temporal distribution of abatement investment across sectors (by delaying the policy), to ensure the efficient allocation of emissions to each sector of the economy (because all sectors face the same carbon price). In contrast, a heterogeneous policy divides the economy into multiple carbon price regimes, where each regime has a different carbon price. The latter approach can itself take two forms, in both relaxing decarbonization initiatives in the sectors facing political constraints (i.e., implementing a sub-optimal carbon price immediately) or by delaying the onset of the optimal carbon price in vocal sectors for some amount of time.

To explore each of these policy scenarios, we formulate four political economy-constrained policy suites that allow us to model each of these approaches to decarbonization. Each policy suite places increasingly stringent constraints on the policymaker, leading to more and more costly policies (we prove a cost ranking of the policy suites we consider in Appendix B). Throughout our discussion, we refer to a delay in either decarbonization or starting climate policy by $\delta T > 0$. Table 1 summarizes the implications of the policy suites we introduce below on model parameters, particularly the carbon price facing each grouping of economic sectors, the policy start times and the decarbonization dates of vocal and non-vocal sectors, as well as the emissions premia required to achieve policy goals.

The first suite we consider is trivial: the "first-best", no political constraints scenario. The planner simply enacts the first-best, optimal policy by solving (2.1). Throughout, we will use this baseline as a way to quantify the impact of political constraints in the other three suites we consider.

The second policy suite involves a heterogeneous policy enacted immediately. We will refer to this policy option as the "immediate heterogeneous" policy. The planner accommodates political headwinds by allocating a premium amount of emissions to the set of vocal sectors, such that the decarbonization dates for the sectors $i \in V$ are shifted by δT, making $T_i = T_i^* + \delta T$. This deflates the carbon price in the vocal sectors and increases the carbon price facing the non-vocal sectors (see Table 1). One interpretation of this policy suite is that the policymaker is pursuing a strategy of "ambition ramp-up" in the politically vocal sectors, where a lower-than-optimal carbon price is enacted immediately and ambition is "ramped-up" in the future. The required emissions premium to achieve this outcome is unique to the vocal sectors in question, see Appendix C. This policy suite characterizes an approach that is focused on preserving the optimal timing of abatement investment (because the policy is enacted immediately) at the expense of the optimal allocation of emissions across sectors.

The third policy suite represents a heterogeneous carbon price policy where the carbon price facing vocal sectors is delayed by some number of years. This policy suite will be referred to as the "delayed heterogeneous" policy option. For non-politically vocal sectors, the policymaker is able to implement policy immediately; hence, $t_{0,i} = 0$ for all $i \in N$. However, in the politically vocal sectors, no policy is able to be implemented for some number of years, implying $t_{0,i} = \delta T$ for $i \in V$. This sets the emissions premium at $B_p = \sum_{i \in V} \bar{a}_i \delta T$ and shifts all the decarbonization dates for $i \in V$ by δT. The carbon price facing the non-vocal sectors is again increased in this policy suite, while the carbon price facing the vocal sectors is the same as the optimal case (the policy is just pushed δT years into the future).

The final policy suite we consider a delayed homogeneous approach, where economy-wide decarbonization initiatives are delayed by some number of years. We refer to this policy suite as the "delayed economy-wide" policy. Since all policies in all sectors are delayed in this approach, we have $t_{0,i} = \delta T$ for all $i \in I$, and the emissions premium is equal to the economy-wide emissions intensity times the delay, $B_p = \sum_{i \in I} \bar{a}_i \delta T$. This is the case, for instance, in nations where climate policy is "held hostage" by some set of economic sectors, or in nations where policymakers are waiting for all political constraints to be removed to implement the first-best (albeit delayed) allocation and sequencing of efforts across sectors. As an example of the latter case, a nation that depends on personal cars for transportation may have strong opposition to climate policies in the transport sector, and this opposition could be so strong that it impacts the entire nation's climate agenda, therefore halting economy-wide climate policy. From a modeling perspective, this approach is equivalent to solving (2.1) with an emissions cap equal to $B - \sum_{i \in I} \bar{a}_i \delta T$, where the total costs are discounted by a factor of $\exp(-r\delta T)$. This policy suite prioritizes the optimal allocation of emissions across economic sectors while sacrificing the optimal timing of abatement investment (by delaying the start of climate policies).

3.2 Cost Ordering of Policy Options

Before carrying out numerical experiments, we present the main theoretical result: that the cost of our policy suites considered in Table 1 are nested.

Theorem 3.1. *Consider* (2.1) *and* (2.4)*. Then for equivalent amounts of delay in the decarbonization of the challenged sectors, the economy-wide delay policy suite is the most expensive sub-optimal policy response to political constraints, followed by the delayed heterogeneous policy, with the immediate heterogeneous policy being the least expensive sub-optimal response for a fixed amount of delay.*

Proof. See Appendix B. □

The intuition for this result is as follows. First, consider the immediate heterogeneous policy and the delayed heterogeneous policy. Both policies delay the decarbonization date of the challenged sector by some number of years. However, in the immediate heterogeneous policy, investments are smoothed out over time, which limits the additional costs of the political constraint that are imposed by adjustment costs (because the investment rate is lower). This is not the case in the delayed heterogeneous policy, where all investments are withheld for the delay period, increasing the additional costs of policy relative to the immediate heterogeneous case.

The delayed heterogeneous policy, in turn, is less expensive than the delayed economy-wide policy. In this case, investments in abatement are delayed for equal amounts of time for each policy. Since investments are only delayed in a subset of sectors for the delayed heterogeneous policy, the required emissions premium is less than in the economy-wide case. This limits the distortion to the optimal allocation of abatement across the economy, making the delayed heterogeneous option less expensive than the delayed economy-wide policy.

Another way of understanding this result is that the sets of solutions over which the policymaker can optimize are nested: the solutions in the delayed economy-wide policy are included in the solution set with the delayed heterogeneous policy, which in turn is included in the solution set with the immediate heterogeneous policy.

4 Simplified Examples

We will now carry out two examples of model behavior to gain intuition for how altering optimal abatement investment strategies to assuage political constraints changes policy outcomes. Throughout this section, we will focus on comparing the first-best policy and the "sectoral, delayed action" policy; later, in our calibrated numerical experiments, we will simulate all four policy suites shown in Table 1. Note that the goal of this section is not to emulate real-world economies, but rather to build an understanding of general model dynamics.

4.1 Two Sector Case

We begin by demonstrating the general behavior of the first-best policy and the delayed, sectoral policy. In the latter case, policy is delayed by five years (i.e., $\delta T = 5$ yrs). We model an economy with two sectors that have the same marginal investment cost and capital depreciation rate, given by $\bar{c} = 10,000$ (\$ / tCO_2) / ($GtCO_2$ / yr^2) and $\delta = 10\%$, respectively, but with differing emissions intensities. The "high emissions" sector has an emissions rate of 4 $GtCO_2$ per year (denoted as $\bar{a}_{hi}$), while the "low emissions" sector has an emissions rate of 2 $GtCO_2$ per year (denoted by $\bar{a}_{lo}$). The discount rate is given by 2% and the carbon budget is 200 $GtCO_2$.[6]

[6]In the *Supplementary Information*, we carry out this same calculation for two sectors where the emissions rates are the same and (1) the marginal investment costs are different or (2) the capital depreciation rates are different, see Figures S1 and S2, respectively.

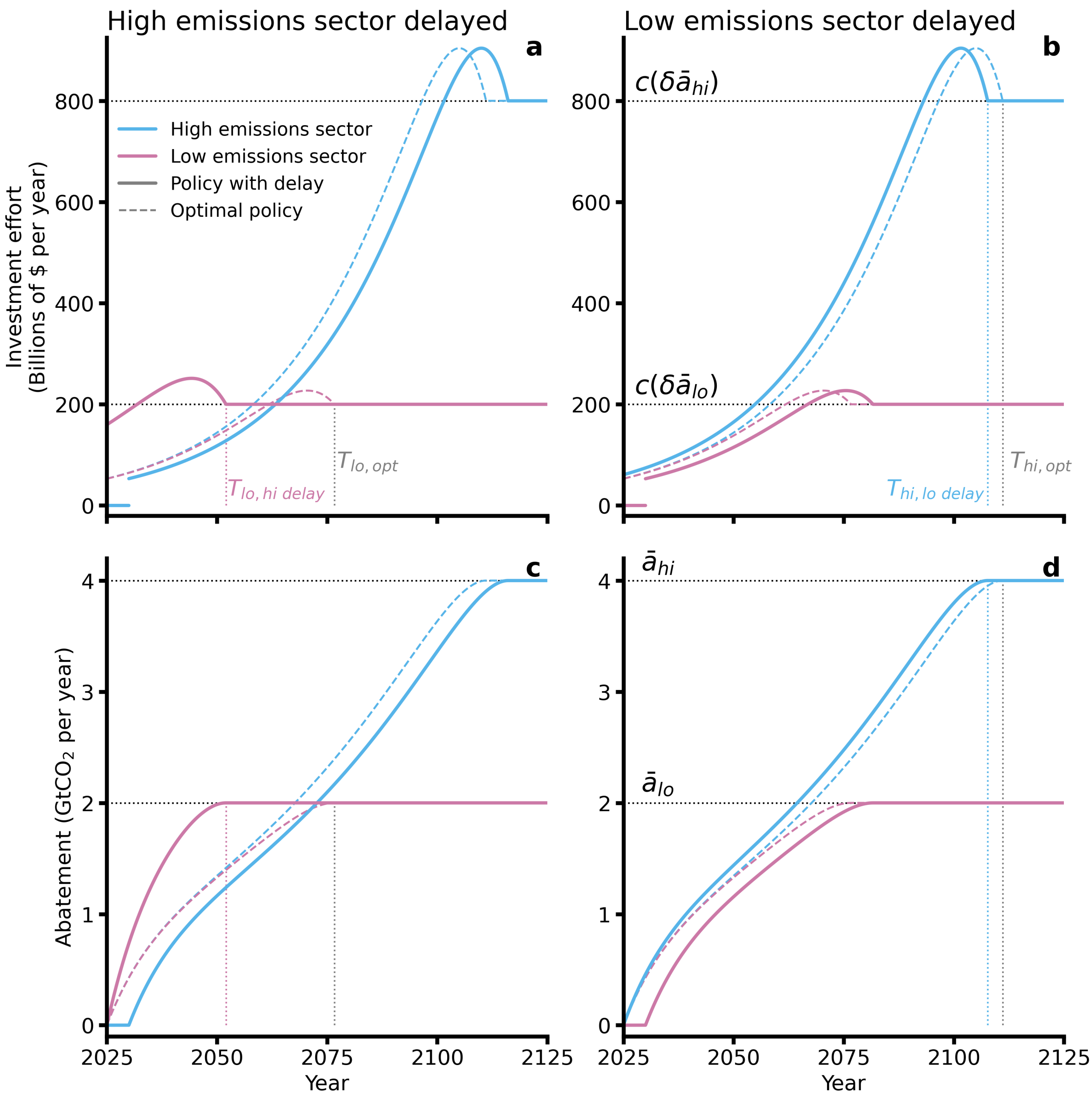

Figure 1. Two Sector Example of Model Behavior. Panel **a** shows the optimal investment effort, $c(x)$, for both sectors in the optimal policy (dashed lines) and in the policy where the decarbonization of the high emissions sector is delayed by five years (solid lines). The high emissions sector investment path is in blue, while the low emissions sector is in pink. The black dotted lines show the steady state investment effort for both sectors (see the labels in panel **b**). Panel **b** is as **a**, but when decarbonizing the low emissions sector is delayed by five years. Panel **c** and **d** show the optimal abatement in each policy case. The black dotted line in panels **c** and **d** show the steady state abatement rate.

The result of this exercise is shown in Figure 1. The left column (panels **a** and **c**) represent the scenario where the high emissions sector is delayed, while the right column (panels **b** and **d**) represent the scenario where the low emissions sector is delayed. In each column, the policy for the high emissions sector is in blue and the policy for the low emissions sector is in pink. The first-best policy is the thin, dashed lines while the policy with delay is given by the solid lines. Figs. 1**a**–**b** show the investment effort, while Figs. 1**c**–**d** show the abatement. Finally, the dotted black lines in Figure 1 show the steady-state values for each quantity as discussed in Section 2, while the colored and grey dotted lines show the decarbonization dates of each sector in the policy with delay and the optimal policy, respectively. Note that the blue, solid line (pink, solid line, resp.) in Fig. 1**a** (Fig. 1**b**, resp.) is the optimal investment path shifted forward by five years, consistent with the delayed, sectoral policy approach (see Table 1).

The first insight shown in Figure 1 is the bell-shaped investment paths mentioned in Section 2.2, see Figs. 1**a**–**b**. Here both sectors have bell-shaped paths, but the rise and fall of their paths is different owing to differing sectoral characteristics, and therefore different marginal implicit rental costs of capital. In our case, the high emitting sector, because of its higher emissions rate, rises slower and peaks later than the low emissions sector. The optimal path of abatement (Figs. 1**c**–**d**) highlights the difference between each sectors' decarbonization date: we see that the high emissions sector is decarbonized after 2100, while the low emissions sector is decarbonized by 2075 or so.

Turning one's attention to the policies with political constraints (solid lines in Figure 1), we show how the sectoral characteristics of the vocal and non-vocal sectors changes the impact of delaying climate policies. When the high emissions sector is delayed (left column in Figure 1), we find that the low emissions sector experiences about a 200% increase in present-day spending. The investment path then raises quicker and peaks sooner than in the optimal case. This change in investment effort is required in order to "make room" in the emissions budget to accommodate the delay of policies impacting the high emissions sector. The overall increase in spending leads to the low emissions sector being decarbonized about 25 years sooner compared to the first-best case, and increases total policy costs by 3.8%.

The impact of delaying the low emitting sector are, by comparison with the high emitting sector, much smaller. The optimal investment pathway of the high emissions sector is quite close to the optimal solution (compare the blue solid and dashed lines in Fig. 1**b**), and the initial level of investment is only increased by about 15%. Likewise, the high emitting sector is decarbonized only 3 years earlier, and total policy costs are increased by just 1.3%, almost a third of the increase in policy costs when policies impacting the high emitting sector are delayed.

The reason that political challenges facing the high emissions sector are more expensive than the low emissions sector can be explained by the emissions premium required to accommodate the political constraint. High emissions sectors require more emissions to be re-allocated to their budgets to accommodate political constraints than do sectors with low emissions intensities (see the final column in Table 1). Consequently, vocal sectors with high emissions rates distort the carbon price impacting non-vocal sectors more than vocal sectors with low emissions rates, thus inducing a more pronounced distortion in the optimal allocation of abatement. In the example above, when the high emissions sector is treated as politically vocal, the carbon price impacting the non-vocal, low emissions sector is increased by 78% relative to the optimal carbon price. As a result, the non-vocal sector is decarbonized 25 years sooner than in the optimal case. When the low emissions sector is vocal, the carbon price impacting the non-vocal, high emissions sector increases by just 7% in comparison. This causes a paltry change in the decarbonization timeline for the non-vocal, high emissions sector, moving it only three years sooner. This asymmetry in the carbon price distortion relative to the optimal explains why high emitting sectors are more expensive to delay than low emitting sectors.

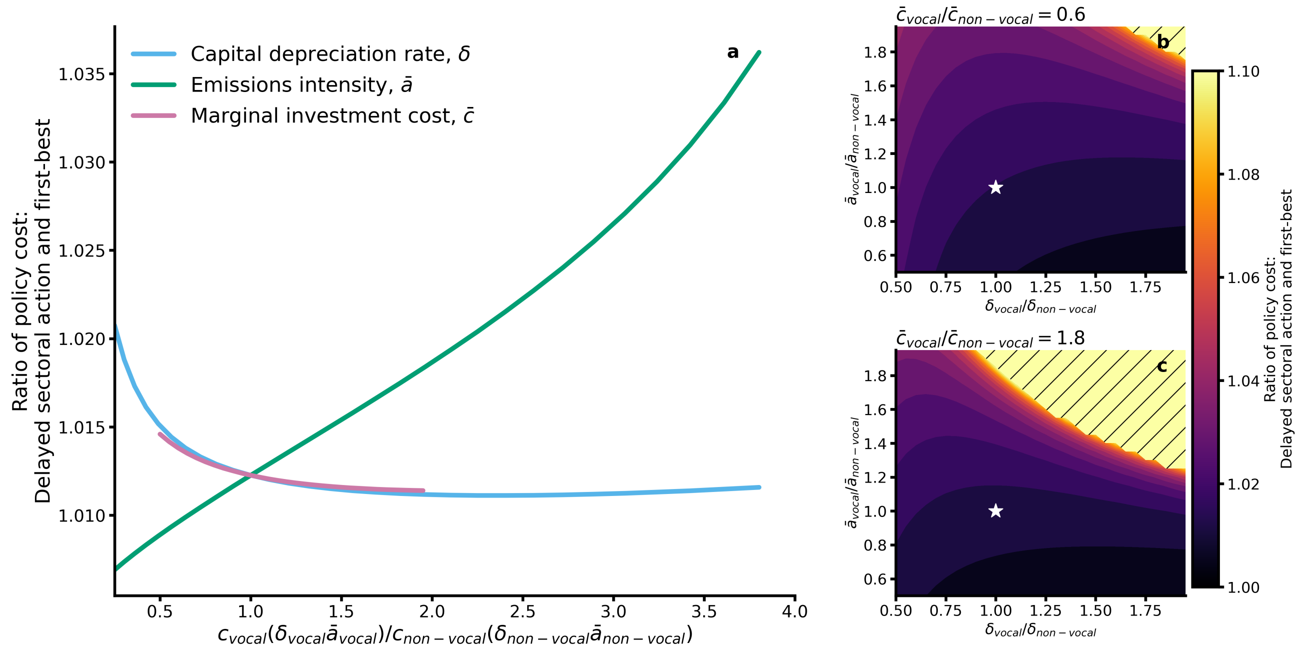

Figure 2. Sensitivity of Policy Cost to Different Sectoral Configurations. Panel **a** shows the ratio of the total cost of the delayed heterogeneous action policy and the optimal policy plotted against the ratio of total abatement value between the vocal and non-vocal sector when we vary one parameter and hold the others constant (the varied parameter is given by the color of each line, see the legend). Panels **b–c** are heatmaps of total policy cost sensitivity to co-varying the emissions intensity and capital depreciation rate of the vocal sector, holding marginal investment costs fixed. See the titles of each panel for the relative marginal investment costs between sectors. Hatching in panels **b–c** represents infeasible parameter combinations (because delaying climate policies causes the carbon budget allocated to the non-vocal sectors to be zero or negative). The white stars in panels **b–c** show the points that are plotted in panel **a**.

4.2 Sensitivity of Policy Cost to Model Parameters

In the above example, we assumed sectors were identical outside of their emissions intensities. But how do model parameters determine the cost of delaying climate policies? We can more rigorously explore the trade-offs between parameters via a sensitivity test. We carry out simulations where we generate 27000 synthetic combinations of the two sector system described above, where the marginal investment cost, emissions intensity, and the capital depreciation rate of the politically vocal sector is varied while we keep the characteristics of the non-vocal sector fixed.

As we discussed above, a key determinant of the cost of delaying climate policies is the relative values of model parameters (in the above case, an asymmetry in emissions rates). This implies that it is not so much the absolute value of the model parameters that matters, but rather the relative values of the parameters between sectors. This supports our choice to keep the non-vocal sector characteristics fixed while varying the vocal sector characteristics. It also implies that, in the numerical simulations below, even if we over- or under-estimate the total costs of decarbonization, our qualitative results on the costs of delay remain unchanged. We vary each parameter such that the marginal investment cost, emissions intensity, and capital depreciation rate vary between being half that of the non-vocal sector to twice that of the non-vocal sector (i.e., for each parameter ξ_{vocal}, we have $\xi_{vocal} \in [0.5 \times \xi_{non-vocal}, 2 \times \xi_{non-vocal}]$).

The results of the sensitivity test are shown in Figure 2. Fig. 2**a** shows the ratio of policy costs in the delayed, sectoral action policy to the first-best policy plotted against the ratio of total abatement value, $c(\delta\bar{a})$, between the vocal and non-vocal sector, when only one parameter is varied. The parameter that is being varied is given by the colors (see the legend). Note the total abatement value is given by the total investment effort in the steady state, and because our cost functions are assumed quadratic, is given by $c(\delta\bar{a}) = \bar{c}\delta^2\bar{a}^2/2$ (see Assumption 1 in Appendix A). Figs. 2**b–c** are heatmaps of additional policy cost when both the emissions rate and the capital depreciation rate are varied (and marginal investment costs are held fixed). We choose to hold marginal investment costs fixed because it induces the least variability in policy costs, as shown by the pink line in Fig. 2**a**. We provide heatmaps where each parameter is held constant in the *Supplementary Information*, see Figure S3.

The first takeaway from this sensitivity test is that the cost of delaying policies is most sensitive to asymmetries in the annual emissions rate of each sector (green line in Fig. 2**a**). This is explained by the emissions premium effect described in the previous example: delaying policies impacting sectors with high emissions rates causes larger distortions in the allocation of emissions between sectors than policies impacting low emissions sectors, therefore leading to higher policy costs. We further find that variability in the emissions rate is dominant even when other parameters are covaried; in Figs. 2**b–c**, we find that, for most parameter combinations, contour levels show more variation along the vertical direction than the horizontal. This implies that asymmetries in the emissions rates between the two sectors is more important for the cost of delaying policies than asymmetries in the capital depreciation rate or marginal investment costs.

The sole exception to this finding is along the frontier where parameter combinations become infeasible, shown by the hatched regions in Figs. 2**b–c**. These infeasible parameter combinations arise when, in order to accommodate the political constraint, the carbon budget of the non-vocal sector becomes zero or negative, therefore making the problem infeasible (i.e., it has infinite cost). The location of this frontier is influenced by both the capital depreciation rate and the emissions rate because of how each parameter impacts the optimal allocation of emissions between sectors. When one sector has a higher capital depreciation rate than the other, more emissions are allocated to the higher depreciation rate sector in the optimal case (because it has a higher total abatement value). Therefore, one needs less of an emissions premium (i.e., a lower value of $\bar{a}_{vocal}/\bar{a}_{non-vocal}$) to arrive at an infeasible policy when $\delta_{vocal}/\delta_{non-vocal}$ is large. The same is true when there are large asymmetries in the marginal investment cost between vocal and non-vocal sectors, which explains why there is more hatched area in Fig. 2**c** than in Fig. 2**b**. As the capital depreciation rates become closer between vocal and non-vocal sectors, the optimal allocation becomes more even, and the emissions premium required to have an infeasible setup increases.

Table 2. Model Calibration. For each sector, we present the annual emissions rate, $\bar{a}$, capital depreciation rate, δ, and the marginal investment cost, $\bar{c}$. We also show the social discount rate, r, and the global carbon budget, B. Note the carbon budget used throughout is for a 1.7 °C global temperature target.

Global parameters:	$r = 2\ \%\ \text{yr}^{-1}$	$B = 625\ \text{GtCO}_2$	
Sector	$\bar{a}\ \left[\text{GtCO}_2\ \text{yr}^{-1}\right]$	$\delta\ [\%\ \text{yr}^{-1}]$	$\bar{c}\ \left[\frac{\$\ \text{tCO}_2^{-1}}{\text{GtCO}_2\ \text{yr}^{-3}}\right]$
Waste	0.82	3.3	12954
Industry	5.47	4	5566
Forestry	8.25	0.8	2259
Agriculture	4.07	5	7567
Transport	3.74	6.7	1942
Energy	11.99	2.5	895
Buildings	3.2	1.7	4122

While we find that the cost of delaying climate policies increases with the emissions rate of the vocal sector, we find the opposite relationship between policy costs and capital depreciation rates and marginal investment costs (pink and blue lines in Fig. 2**a**).[7] The rationale behind this result is that, when the marginal investment cost of the vocal sector is less than the marginal investment cost of the non-vocal sector (thus $c_{vocal}(\delta_{vocal}\bar{a}_{vocal}) < c_{non-vocal}(\delta_{non-vocal}\bar{a}_{non-vocal})$), delaying the cheaper sector causes more effort up-front in the expensive sector. Adjustment costs make this additional up-front effort in the more expensive sector costly. The implications are the same for the relative capital depreciation rates of the sectors, because the total abatement value depends quadratically on the capital depreciation rate. This explains why the capital depreciation rate causes more variability in total policy costs than marginal investment costs (i.e., the blue line varies more than the pink line in Fig. 2**a** over identical relative parameter ranges). Overall, we find that these effects are smaller than the emissions premium effect examined earlier, but explain why, when emissions rates between sectors are the same, we find an inverse relationship between policy costs and relative marginal investment costs (or relative capital depreciation rates).

5 Calibrated Numerical Experiments

5.1 Design

We now present model simulations calibrated to the global economy. We discuss the details of our calibration scheme in Appendix D and show the model parameters used throughout in Table 2.[8] In all of the results we show below, the planner aims to decarbonize the world economy such that global average temperatures do not breach 1.7 °C in the long-run, in compliance with the Paris Agreement warming targets (United Nations Framework Convention on Climate Change, 2015).[9]

[7] Recall that along the pink and blue lines in Fig. 2**a**, the emissions premium is held constant because the emissions rates of the sectors are fixed.

[8] Note that throughout the paper, all dollar values are in 2020 USD.

[9] Note that we do not consider direct air capture technologies in our analysis. This is because of their high cost relative to other abatement options. Our experiments thus model the "worst case" scenario for policy costs, as if the cost of direct air capture technologies decline in the future, overall costs would decrease as some expensive mitigation options would not be pursued in favor of direct air capture.

One important note on our calibration is that we treat all emissions from energy consumption as emissions attributed to the energy sector. This implies that emissions required to charge electric vehicles are attributed to the energy sector, not the transport sector; rather, transport sector emissions would arise from driving a combustion engine vehicle, for example. Therefore it is possible within the model to "decarbonize" transport (when the entire vehicle fleet turns over from gas-fired combustion engines to electric vehicles) even if the energy sector itself is not yet fully decarbonized (meaning some electricity used to charge the electric vehicle fleet is dirty). One could argue that this implies that the transport sector is not yet fully decarbonized, but from an abatement capital perspective, there are no further investments required within transportation sector that can lower its emissions; the remaining capital installations must be in energy generating capital stocks, like advanced nuclear, wind turbines, and solar arrays. We provide a breakdown of mitigation options by sector in Table S1 of the *Supplementary Information*.[10]

We will begin our numerical simulations by focusing on two sectors as being politically vocal: energy or industry. Our motivation is that energy is the sector with the highest annual emissions rate, implying that delaying this sector would require the largest reallocation of emissions across the economy. As discussed in Section 4, the emissions rate of the vocal sector is a key driver of the cost of delaying climate policies. Therefore, treating energy as politically vocal will allow us to probe the upper bound of the costliness of our political constraints. Industry, on the other hand, has a moderate emissions rate (about half that of energy), but is over six times as expensive in terms of marginal investment costs compared to energy. Its capital depreciation rate is also about twice that of energy. Therefore, these two sectors provide useful guideposts for our discussion, where energy signifies delaying a cheap sector with substantive annual emissions, whereas industry represents delaying a sector with moderate emissions but with high total abatement value.

From a narrative perspective, modeling delay in the energy sector could represent a situation n which fossil fuel subsidies prove difficult to reform, while delaying heavy industry could represent a nation that is concerned about the competitiveness of domestic industries and therefore delays the decarbonization of its industrial sector. We will explore the impact of delaying decarbonization for each sector listed in Table 2, and relate this to their sectoral characteristics, at the end of this section.

To summarize, our experiments solve for the optimal abatement investment schedule in each policy scenario described in Table 1 with either energy or industry serving as the politically vocal sector (i.e., each set of simulations are carried out independently, with one politically vocal sector). This means we solve either (2.1) or (2.4) with a specified δT amount of delay. We repeat this process for a number of $\delta T \in (0, 10]$ with a discretization of 0.1 years.

5.2 Results

We begin by showing the optimal investment pathways when energy is treated as politically vocal in Figure 3. (We provide an analogous figure for when industry is treated as politically vocal in the *Supplementary Information*, see Figure S4.) The grey solid lines show the first-best investment path, the blue dash-dot lines show the immediate heterogeneous action policy approach, the blue solid lines show the delayed heterogeneous option, and the pink dotted lines show the economy-wide delay approach. For each path in Figure 3 we set $\delta T = 10$ years, implying a ten year delay in the decarbonization of the energy sector in the immediate heterogeneous action path, a ten year delay in instituting the optimal climate policy in the energy sector for the delayed heterogeneous policy, and a ten year delay in enacting the optimal economy-wide policy in the delayed economy-wide option.

Figure 3 highlights the qualitative similarities and differences between the policy suites. We further quantify the size of the emissions premia required for each policy suite in Table 3, as well as the total emissions cap for the vocal and non-vocal sectors and the relative change in the emissions allocation

[10] See also the Technical Summary, Chapter TS5, Section 9, "Mitigation Potentials Across Sectors and Systems", p. 123-125 and figures therein of Intergovernmental Panel on Climate Change (2022) for further information.

Table 3. Emissions Premia and Emissions Caps for vocal and non-vocal Sectors in Each Policy Suite. Shown is the emissions premia (B_p), the emissions cap for the vocal sectors (B_{vocal}), and the emission cap for the non-vocal sectors ($B_{non-vocal}$) in each policy suite when either energy or industry is treated as politically vocal. In the B_p, B_{vocal} and $B_{non-vocal}$ columns, the first value is in $GtCO_2$, while the parenthetical values are percent changes relative to the optimal allocation. Note the emissions cap for the vocal sectors in the delayed economy-wide action option is the economy-wide cap after the delay period, i.e., is $B - B_p$.

Policy Suite	Vocal Sector	5 years of delay			10 years of delay		
		B_p	B_{vocal}	$B_{non-vocal}$	B_p	B_{vocal}	$B_{non-vocal}$
Immediate Heterogeneous	Energy	23.6	146.4 (+19.2%)	478.6 (−4.7%)	48.0	170.8 (+39.1)	454.2 (−9.56%)
	Industry	15.5	172.0 (+9.9%)	453.0 (−3.3%)	31.8	188.3 (+20.3%)	436.7 (−6.79%)
Delayed Heterogeneous	Energy	60.0	182.7 (+48.8%)	442.3 (−11.9%)	119.9	242.7 (+97.7%)	382.3 (−23.9%)
	Industry	27.4	183.9 (+17.5%)	441.1 (−5.8%)	54.7	211.2 (+35.0%)	413.8 (−11.7%)
Delayed Economy-wide	All	187.7	437.3 (−30%)	N/A	375.4	249.6 (−60%)	N/A

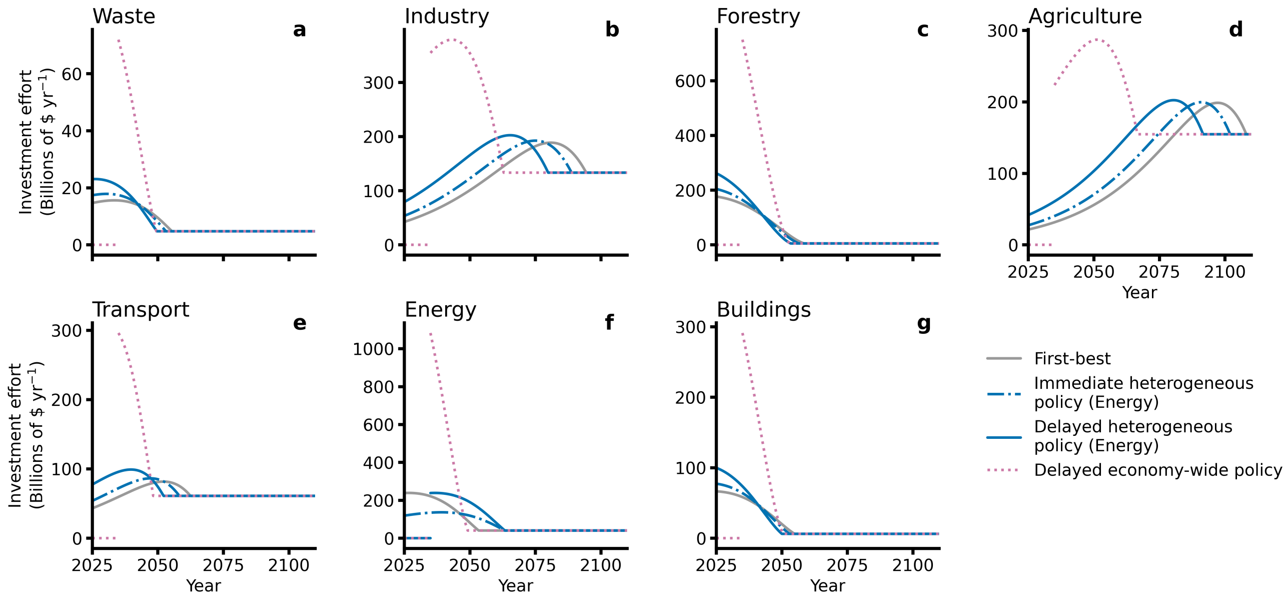

Figure 3. Investment Paths. Panels show the optimal investment path in each sector (see the titles) when energy is treated as the politically vocal sector. The first-best path is given by the solid, grey lines; the immediate heterogeneous path is given by the blue dash-dot lines; the delayed heterogeneous path is given by the blue solid lines; and the delayed economy-wide path is given by the pink dotted line.

to each group of sectors. The immediate heterogeneous policy paths (dash-dot lines in Figure 3) show smaller changes in the investment pathways of the non-vocal sectors than the delayed, sectoral paths (solid lines in Figure 3). This is consistent with the immediate heterogeneous policy requiring a smaller emissions premium to accommodate the political constraint than the delayed, sectoral approach (see Tables 1 and 3), resulting in smaller carbon price distortions and thus changes in investment paths. Changes in the investment paths induced by the immediate or delayed heterogeneous options, however, are dwarfed by changes caused by the economy-wide delayed action approach. This is because the emissions premium required to enact this approach is over three times as large than delaying energy alone (because energy accounts for about a third of total emissions). As discussed in Section 4, larger emissions premiums lead to larger distortions in carbon prices, and therefore bigger changes in the optimal investment path. (We quantify the changes in the carbon price facing vocal and non-vocal sectors as a result of each policy suite in the *Supplementary Information*, see Figure S5.)

Examining the investment path of energy in the immediate and delayed heterogeneous action policy options (dash-dot and solid blue lines in Panel 3**f**) shows how the investment path for the politically vocal sector differs between the two approaches. For the immediate heterogeneous policy, investment is smoothed out over time to accommodate the political constraint. On the other hand, in delayed heterogeneous policy, the optimal investment strategy is shifted by a decade, and no changes are made to the investment schedule once the policy is enacted a decade hence. This partially explains why the cost of the immediate heterogeneous approach is less than the delayed heterogeneous approach: the planner can "smooth out" the political constraint by smoothing investment over time, which cannot be done when all policies impacting vocal sectors are delayed.

One can visualize the magnitude of changes in the investment paths by computing the decarbonization dates of each sector relative to the optimal in each policy suite, as shown in Figure 4. We find that sectors with low total abatement value (such as waste and buildings) have smaller changes in their decarbonization dates than sectors with large total abatement value (such as agriculture and industry). In particular, the observed change in the decarbonization date of high total abatement

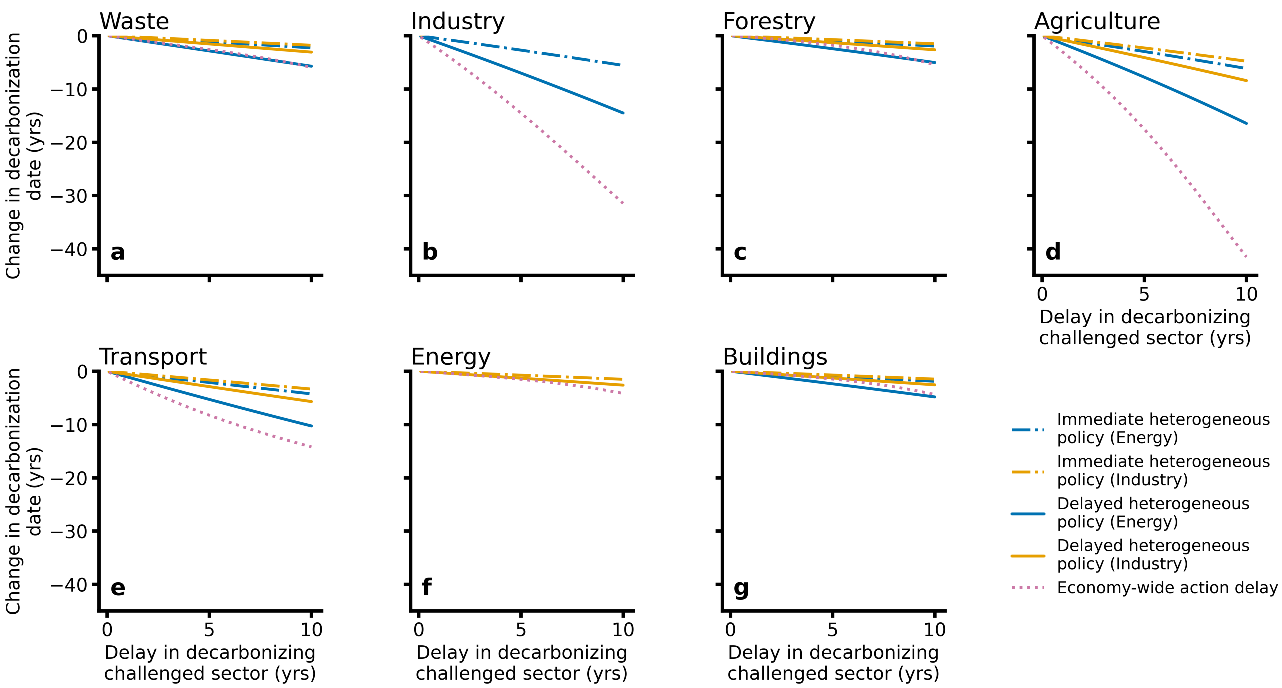

Figure 4. Decarbonization Dates. Panels show the change in decarbonization date of each sector when energy or industry is treated as the politically vocal sector. Orange lines show results when industry is politically vocal, while blue lines show results when energy is treated as politically vocal. Results from the immediate heterogeneous policy are given by the dash-dot lines; results from the delayed heterogeneous policy are given by the solid lines; and results from the delayed economy-wide policy are given by the pink dotted line.

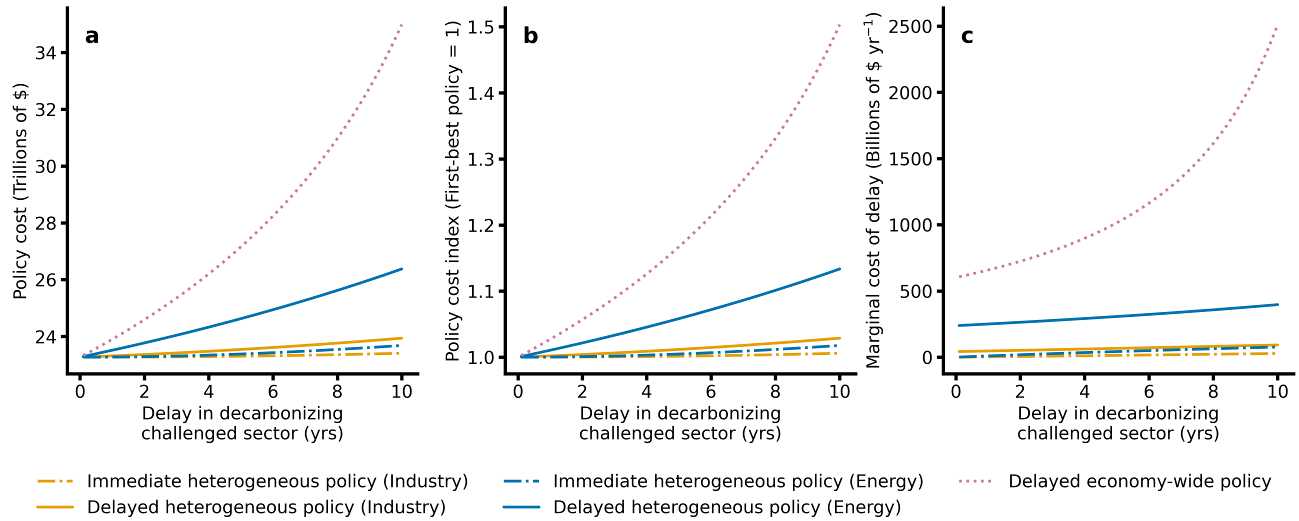

Figure 5. Aggregate Cost Implications of Delay in Each Policy Suite. Panel **a** shows the total policy cost for each policy suite as a function of delay. Panel **b** shows the relative change in cost to the optimal policy cost. Panel **c** shows the marginal cost of delay across each policy suite, calculated as the derivative of policy cost with respect to delay (i.e., the slope of each line in Panel **a**).

value sectors approaches 40 years in the delayed economy-wide action approach, whereas low total abatement value sectors experience more modest changes in their decarbonization dates; relative to the optimal policy, the decarbonization dates these sectors decreases by at most 7 years. This is because, when decarbonization needs to be sped up in non-vocal sectors to accommodate political constraints in vocal sectors, sectors that decarbonize relatively quickly in the optimal least-cost policy (such as waste, buildings and transport) cannot be further accelerated because adjustment costs would make this prohibitively expensive. This leads to more effort being siphoned towards sectors with high total abatement value (which have a low initial level of investment, see Figure 3), implying larger changes in the decarbonization dates of those sectors.

We further find that, as expected, treating industry as politically vocal leads to less changes in decarbonization dates than when energy is treated as politically vocal. For example, treating energy as politically can lead to the agricultural sector decarbonizing about 15 years sooner, whereas treating industry as politically vocal can lead to agriculture decarbonizing only 9 years sooner. This is a result of the different sizes of emissions premia and distortions in the optimal allocation of emissions required to accommodate political challenges facing either sector (see Table 3). This supports our previous argument that the emissions rate of the politically vocal sector is the leading-order contributor to the cost of delaying climate policies impacting the vocal sector. The costliness of delaying climate policies impacting industry is further suppressed by its higher total abatement value relative to energy.

The changes in optimal investment paths and decarbonization dates results in higher overall policy costs, which we show in Figure 5. We show the policy cost in Fig. 5**a**, the ratio of the policy cost to the first-best in Fig. 5**b**, and the marginal cost of delaying policy in a given sector in Fig. 5**c**. Note that we compute the marginal cost of delaying policy in a given sector by taking the derivative of Fig. 5**a** with respect to the amount of delay.

Our first finding from Figure 5 is that the quantitative implications of delay for the immediate heterogeneous policy are small in comparison to the other policy suites. For energy, we find that delaying decarbonization by a decade in the immediate heterogeneous policy results in just a 1.7% increase in overall policy costs, and a 0.6% increase for delaying industry for a decade; in monetary terms, this implies increases of a \$410 billion and \$140 billion in cost, which is dwarfed by the \$11.7 trillion increase by a decade of delay in economy-wide delay policy. The difference between monetary

Table 4. r^2 Values for Regressions Between Parameter Values and Relative Policy Cost After Delay, Shown in Figure 6.

Policy suite	Delay amount (years)	δ	$\bar{a}$	$\log_{10}(\bar{c}_i)$
Immediate heterogeneous action	5	0.28	0.95	0.61
	10	0.26	0.97	0.69
Delayed heterogeneous action	5	0.32	0.89	0.69
	10	0.28	0.92	0.69

impacts in the immediate heterogeneous policy, as opposed to the delayed heterogeneous or economy-wide policy, results from *some* degree of action being taken immediately. This allows the policymaker to smooth investment over time, which is not possible when all action in the challenged sectors is delayed. As a result, relaxation-based policies require far less emissions premiums to accommodate delay, thus limiting their impact on aggregate policy costs.

Our second finding is that the aggregate economic cost of policy increases nonlinearly as decarbonization in the vocal sector(s) is delayed. This can be shown most succinctly in Panel 5**c**, where we find the marginal cost of delaying decarbonization to be increasing in delay. This result is perhaps not surprising given the presence of adjustment costs: as decarbonization in the vocal sector(s) is increasingly delayed, the more non-challenged sectors are squeezed to decarbonize sooner, which adjustment costs make nonlinearly more expensive. The requisite decrease in spending in the vocal sector cannot account for the increasing expenses in the non-vocal sectors, leading to a higher overall cost of policy. Another interpretation of Figure 5 is that when all policies are delayed (as in delayed economy-wide action policy), objectives becomes increasingly difficult to achieve without strong, costly action. With a smaller delay, or a sub-optimal set of policies in politically challenged sectors (*à la* the immediate or delayed heterogeneous approaches), the increase in cost remains roughly linear and thus less costly than the delayed economy-wide option.

Finally, despite their qualitative similarities, we find significant quantitative variation in the aggregate policy cost across policy suites. For the delayed economy-wide policy suite, aggregate policy costs can increase by as much as 50% (see Panel 5**b**), and the marginal cost of delay (Panel 5**c**) can exceed \$2.5 trillion per year of delay. In the immediate or delayed heterogeneous policies, we find that increases in the aggregate policy cost are much less than in delayed economy-wide policy case: the marginal cost of delay is a maximum of \$76 billion or \$397 billion per year for the immediate or delayed heterogeneous policies, respectively.

We carry out the same analysis above treating each sector as politically vocal and compute the cost of delay for each case in Figure 6. We find similar results as presented in our sensitivity analysis in Section 4: the additional policy cost of delay is increasing in the emissions rate of the vocal sector and decreasing in the marginal investment cost and capital depreciation rate of the vocal sector. However, we find a much higher correlation between policy costs and emissions rates than we do policy costs and marginal investment costs or capital depreciation rates (see Table 4). This result suggests that it is the size of the emissions premium required to accommodate political constraints, rather than the total abatement value of sectors, that wins out in determining the cost of political constraints in climate policies.

One important implication of this result is that, in real-world settings, energy is the most expensive sector to delay acting in. We find this to be true for both the immediate heterogeneous policy and the delayed heterogeneous policy. The fact that energy has the lowest marginal investment cost and a relatively low capital depreciation rate further bolsters the cost of delaying policies aimed at decarbonizing

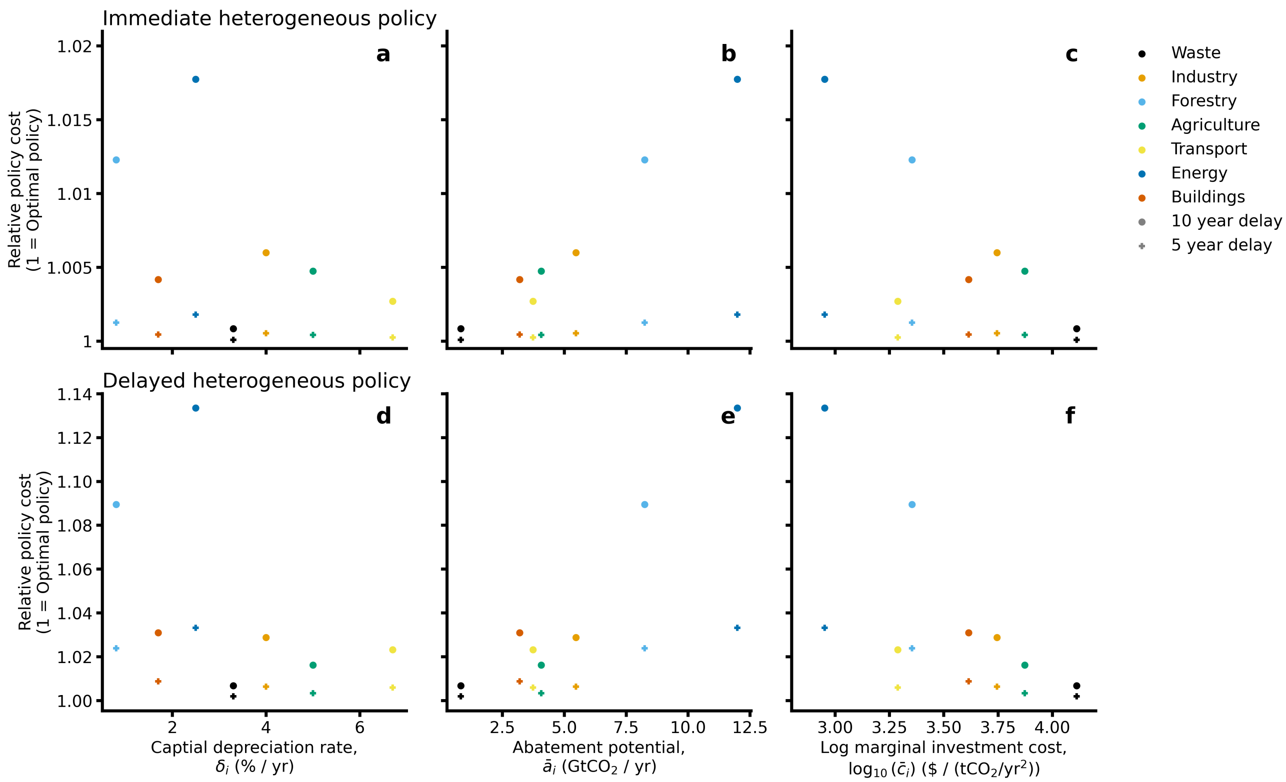

Figure 6. Increase in Policy Costs Treating Each Sector as Politically Vocal. Panel **a** shows the relative policy cost between the immediate heterogeneous policy and the first-best when each sector is treated as politically vocal, plotted against the capital depreciation rate of the sector; each sector is represented by a colored dot. Circular dots represent results from a 10 year delay, while pluses represent results for a five year delay. Panels **b, c** are as **a**, but plotted against the emissions rate and the logarithmic marginal investment cost of the vocal sector, respectively. Panels **d–f** are as **a–c** but for the delayed heterogeneous action policy option.

it. Indeed, energy is the "perfect" sector, as described by our analysis, to have a large cost of delay: it has a high emissions rate, leading to high emissions premia, and a low marginal investment cost and capital depreciation rate, leading to more effort happening in the expensive sectors to accommodate political constraints in the energy sector.

6 Discussion

We close by summarizing the key findings of this paper, discussing the implications of our results for policy, offer some caveats to our analysis owing to factors excluded from our modeling approach, and propose future directions.

6.1 Summary of Key Findings

Our first contribution is to present a model that incorporates political constraints into optimal decarbonization investment strategies. We used this model to quantify the cost of delaying climate policies towards reaching some climate goal (in this case, limiting cumulative emissions below the carbon budget). Our model captures the influence of adjustment costs, broadly defined as economic factors that make transitioning quickly away from fossil fuel use more expensive than transitioning slowly (such as supply constraints on technologies or labor training and re-training costs).

We then outlined four policy suites that involve delaying climate action, both at a sectoral level and across the economy, and utilized our model to quantify the cost of each of these scenarios. We carried out two sets of numerical simulations: one set of simulations with synthetic two-sector configurations to understand what sectoral characteristics drive the cost of delaying climate policies; and one set of simulations calibrated to International Panel on Climate Change (IPCC) data on abatement costs, emissions rates, and carbon budgets to understand how the broad characteristics of the global economy impact the costliness of delay.

The primary insight from our simulations using synthetic two-sector economies is that there are two mechanisms by which delaying climate policies in one sector can impact the overall cost of policy: (1) the size of the emissions premium required to accommodate the political constraint, and (2) the relative total value of abatement between the two sectors.

The size of the emissions premium dictates how much of the total emissions cap needs to be redirected to politically vocal sectors to assuage political constraints. Politically vocal sectors with high emissions rates require a larger emissions premium (and therefore a larger distortion in abatement efforts relative to the optimum) to accommodate political constraints than politically vocal sectors with low emissions rates. Therefore, delaying sectors with large emissions rates leads to higher carbon prices facing the non-politically vocal sectors, which then leads to the especially rapid decarbonization of the non-vocal sectors. Adjustment costs make this increased pace of decarbonization in low emissions sectors even more costly. These findings are likely to also hold in a cost-benefit setting, as delaying high emissions sectors would lead to more near-term temperature rise and therefore more economic damages than delaying low emissions sectors (because cumulative emissions are linearly linked to temperature rise via the transient climate response to emissions, as discussed in Matthews et al. (2009) and Intergovernmental Panel on Climate Change (2021)).

The relative value of abatement between the politically vocal and non-vocal sectors explains why delaying cheap (or fast-depreciating) sectors is more expensive than delaying expensive (or slow-depreciating) sectors, conditional on the same emissions rate for the sectors. When a low total value of abatement sector is delayed, high value of abatement sectors are forced to decarbonize sooner. Because costs are higher in those sectors, forcing a premature decarbonization of expensive sectors is more costly than prematurely decarbonizing cheap sectors, especially in the presence of adjustment costs. Our experiments suggest that the impact of large emissions premia is roughly double that of the relative abatement value between sectors.

Our IPCC-calibrated experiments also showed that the impact of large emissions premia described above is dominant compared to the relative value of abatement between sectors. The main finding from these experiments is that the energy sector has all the characteristics of a sector which is expensive to delay: it has high emissions (almost twice that of the next closest sector in our calibration), low marginal investment costs, and a relatively low capital depreciation rate. This intuition complements previous work that highlights the importance of decarbonizing the power sector for other reasons, such as meeting climate goals and enabling the decarbonization of high energy demand sectors such as passenger transport (Williams et al., 2012; Audoly et al., 2018). These calibrated numerical experiments thus support the findings from our synthetic numerical simulations: that the most expensive sectors to delay climate action in are those with high emissions rates. This insight provides a "rule of thumb" for policymakers navigating the political and economic landscape of decarbonization.

6.2 Implications for Policy

Our quantitative results in Section 5 underscore the relative economic costs for different deployments of delay as a policy instrument. On the one hand, we find that delaying decarbonization across sectors can increase the cost of the green transition by as much as 50%. On the other hand, relaxing action in politically challenging sectors can have modest cost impacts, increasing the cost of policy by at most 1.7% for a decade of delay. In this way, our results highlight that the tactical use of delay, as demonstrated in the immediate heterogeneous action approach, can have a low additional cost while complying with political constraints, whereas the "brute force" application of delay (as in the delayed heterogeneous or economy-wide policies) can have larger additional costs.

These findings underscore how implementing a sub-optimal policy in the near-term is more cost-effective than waiting to implement a more efficient policy in the future. Comparing the difference in cost between relaxing or delaying decarbonization in the energy sector supports this point: the difference in the additional policy cost between the two approaches is $\sim$ \$2 trillion (granted this difference is smaller for less emissions-intensive sectors, like industry). Of course, each of these options are better than delaying all climate policies.[11] We conclude that, if a policymaker were facing political headwinds while still wanting to achieve climate goals, implementing a sub-optimal carbon price or ETS that delays the full decarbonization of vocal sectors may be an attractive policy approach. This conclusion would support the idea of exemptions for politically sensitive sectors if and only if they make it possible to implement the policy sooner.

Our final note is that it is not clear that the "brute force" application of delay is, in the long run, politically expedient. This is because, for the delayed heterogeneous or economy-wide policy approaches, the policy implemented after the delay period must be at least as stringent as the optimal policy in order for the policymaker to remain compliant with the emissions cap; in the case of the delayed economy-wide policy, the required policy could be significantly more stringent than the optimal policy. Also, the costs of delay rise at different rates between sectors (see Figure S6 in the *Supplementary Information*), meaning that delaying policies because of currently-vocal sectors may cause additional sectors to become vocal later after the delay because of rising policy costs. Therefore, the political environment after the delay period not only has to be amenable to the original optimal policy in the delayed sectors or across the entire economy, but it may require an environment that is exceedingly (perhaps unreasonably) favorable so that an even more stringent carbon price can be implemented.

[11] One possible exception to this conclusion could be policies which are administratively burdensome and do not lead to tangible emissions reductions. In this case one would have the worst of both worlds: nontrivial costs and a reduced remaining carbon budget, which would demand an accelerated and costly policy schedule later to remain compliant with the emissions budget.

6.3 The Influence of Technology Change

One aspect of decarbonization policies not explicitly addressed in our analysis is endogenous technology change (Hogan and Jorgenson, 1991; Armitage et al., 2023).[12] Endogenous technological progress is spurred by investments in a given sector or technology and can greatly impact the allocation of investment over time (Kverndokk et al., 2004; Schmidt and Sewerin, 2017; Gillingham and Stock, 2018). Nowhere have the effects of induced technical change been more pronounced than in photovoltaic solar panels, the cost of which have declined substantially over the last decade plus (Bollinger and Gillingham, 2019). Recent work has further shown that learning-by-doing and knowledge spillovers substantially boost global welfare gains as a result of the United States' Inflation Reduction Act (Arkolakis and Walsh, 2023). Endogenous technology change can be modeled in various ways, ranging from agent-based approaches that capture decision-making about research and development in green and dirty technologies (Acemoglu et al., 2012) to macro-level, knowledge accumulation-based approaches (e.g., Goulder and Mathai, 2000); see Coppens et al. (2024) for a review of the role of technology change and its various representations in integrated assessment models.

While not modeled explicitly, we can comment on how our results would interact with endogenous technology change.[13] The first clear implication is that, since the rate of endogenous technological progress depends on the cumulative amount of investment in a given sector (akin to "Wright's law" (Wright, 1936)), delaying investment in sectors with high rates of endogenous learning would be more costly than delaying sectors with low rates of learning. The same argument applies to sectors with high degrees of inter-sectoral knowledge spillovers, such as energy (Richels and Blanford, 2008). Finally, having a credible carbon price in place, even if temporarily deflated, may spur additional private sector investment in abatement technologies (Brunner et al., 2012) which could bring down costs. This would reinforce two main conclusions from our analysis: (1) that pursuing climate action, even if this action is allocated sub-optimally across the economy, is better than delaying policies in order to enact the optimal policy down the road, and that (2) energy is the most expensive sector to delay, given its high rate of endogenous technological growth and potential for knowledge spillovers to other sectors.

6.4 Alternative Policy Instruments

One important aspect of formulating climate policies under political constraints that is not considered in our analysis is the role of regulations or clean energy subsidies (Fischer and Newell, 2008; Armitage et al., 2023) or how stranded assets impact the transition (Rozenberg et al., 2020). Policies focused on providing subsidies for green technology research, development and deployment – or "green industrial policies" (Hallegatte et al., 2013) – have risen in popularity as a way to address climate change while bolstering other national objectives such as job creation or industrial competitiveness. Indeed, both the Inflation Reduction Act (IRA) in the United States and the European Union's Green Deal Industrial Plan explicitly link building up clean energy capital and increasing access to clean-energy technologies to creating "good-paying union jobs" (in the case of the US IRA; The White House, 2023)[14] or "contributing quality jobs and [...] improving the competitiveness of the Union" (in the case of the EU's Green Deal Industrial Plan; The European Union Council, 2024). Further advocates of green industrial policies argue that such approaches build "clean coalitions" of businesses and labor that bolster support of more stringent climate policies later on, as was the case in California and Sweden prior to the enactment of their carbon price mechanisms (Wagner et al., 2015; Meckling et al., 2017). Finally, clean subsidies, used in concert with carbon prices, are a part of the first-best policy mix when

[12]Although, in Appendix A, we do show that an economy-wide, exogenous rate of technological progress, $0 \leq \varphi \leq 1$, is equivalent to a shift in the social discount rate, $r \rightarrow r + \varphi$.

[13]We note that our assumption of constant baseline emissions relies on the assumption of increasing energy efficiency to offset growth effects on emissions, see Appendix D.

[14]Note the link to this article is now inactive owing to recent government policies in the United States.

sufficient positive innovation externalities are present (as a result of the Tinbergen rule; Acocella et al., 2018) even in the absence of political considerations.

Despite green industrial policies being outside the scope of our model,[15] we can comment on how our results might be impacted by including subsidies for clean technologies. First, green industrial policies could be considered as isolated sectoral policies akin to our immediate heterogeneous policy option, in that both the green industrial policy and the deflated carbon price are sub-optimal policies that are enacted only in politically vocal sectors (as opposed to delaying all climate policies impacting the vocal sectors). The key difference would be that, if a green industrial policy is enacted prior to a carbon price, the sectoral marginal abatement costs would change because of the subsidy-induced efficiency gains. Once the carbon price is enacted, our results would then suggest that delaying or relaxing carbon prices facing cheap sectors is more expensive than delaying carbon prices in expensive sectors. The prudent policy response in that case would perhaps be to phase-down (or "sunset") subsidies in low mitigation cost sectors in favor of the carbon price, while ramping-up (or "sunrising") subsidies in the expensive sectors. This would strike a balance between the results presented here that focus on which sectors are most expensive to exempt from a carbon price, and the additional complexities that green industrial policies aim to address.

A final note is that, from a modeling perspective, one can view the lowering of the carbon price as a form of subsidy. The difference here is that subsidies are allocated in a zero-sum setting between sectors: subsidies allocated to politically vocal sectors (via a lower carbon price) are provided to the detriment of politically non-vocal sectors (via a higher carbon price).

6.5 Future Directions

We imagine many extensions of the present work. For one, future work could include the myriad other risks present in the climate-economic system that are not discussed here, such as climate uncertainty (Bauer et al., 2025), transition risk (Campiglio et al., 2022; Barnett, 2023), and climate tipping points (Dietz et al., 2021). One can easily imagine the prospect of delaying decarbonization interacting with each of these risks to exacerbate the economic costs of delay and reinforce the central findings of this paper. Secondly, here we represented climate policies as a carbon price (implemented through an ETS), but, as discussed above, other policy instruments could be added to the policy suites we discuss. Future work could also quantify the additional economic cost of missing technology and knowledge gains as a result of delaying climate policy. Finally, while our numerical examples take a global view, it would be interesting to apply this framework to country-level nationally determined contributions to the Paris Agreement. This could shed light on how the constitution of an individual nation's economy either exacerbates or nullifies the increase in policy costs described here. This is especially the case as the emissions intensity of each sector can vary substantially across countries, meaning that the costliest sectors to delay are bound to change based on the specifics of the economy being examined.

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[15] Including subsidies in our model would likely yield limited qualitative insights. As we consider a partial equilibrium framework, we would not capture the impact of subsidies on, for example, government balances, prices, and requisite interest rate effects. These effects would non-trivially impact the time-path of investments across sectors.

Author contributions

AMB, SH, and FM conceived of the study. AMB carried out theoretical calculations, numerical simulations, and wrote the first draft of the manuscript. SH and FM provided guidance and acquired funding for the project. All authors contributed to editing the final manuscript.

Declarations

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Competing Interests or other Declarations

The authors have no competing interests to declare that are relevant to the content of this article.

Data Availability Statement

There are two options to access the code and data in this paper:

1. The World Bank Reproducible Research Repository: Bauer et al. (2024a)
2. The lead author's Github: `https://github.com/adam-bauer-34/BHM-pol-econ-reprod`

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A Analytical Solutions

The present value Hamiltonian of (2.4) can be written as

$$\mathcal{H} = \sum_{i\in\mathcal{I}} c_i(x_i(t)) + \sum_{j\in\{V,N\}} \left(\mu_j(t)\left[\sum_{i\in j}(\bar{a}_i - a_i(t))\right]\right) + \sum_{j\in\{V,N\}} \left(\phi_j(t)\left[\sum_{i\in j} B_i^* + \sigma_j B_p - \psi_j(t)\right]\right)$$
$$+ \sum_{i\in\mathcal{I}} \nu_i(t)\left(x_i(t) - \delta_i a_i(t)\right) + \sum_{i\in\mathcal{I}} \lambda_i(t)\left(\bar{a}_i - a_i(t)\right), \tag{A.1}$$

where $\mu_j(t)$ is the carbon price facing the sectors $j \in \{V, N\}$, and $\nu_i(t), \lambda_i(t)$ and $\phi_i(t)$ are the remaining Lagrange duals.

The first order condition for the sector $i \in I$ reads

$$\frac{\partial \mathcal{H}}{\partial x_i(t)} = c_i'(x_i(t)) + \nu_i(t) = 0 \tag{A.2}$$

where $' := \partial/\partial x_i(t)$. This implies that

$$c_i'(x_i(t)) = -\nu_i(t) = |\nu_i(t)|, \tag{A.3}$$

where it follows from the fact that $c'(x_i(t)) > 0$ (convexity of the cost function) that $\nu_i(t) < 0$ for all $i \in \mathcal{I}$. Eqn. (A.3) can be interpreted as the marginal cost of abatement capital being equal to the marginal value of a unit of abatement capital stocks.

We can then alter (A.1) such that

$$\mathcal{H} = \sum_{i\in\mathcal{I}} c_i(x_i(t)) + \sum_{j\in\{V,N\}} \left(\mu_j(t)\left[\sum_{i\in j}(\bar{a}_i - a_i(t))\right]\right) + \sum_{j\in\{V,N\}} \left(\phi_j(t)\left[\sum_{i\in j} B_i^* + \sigma_j B_p - \psi_j(t)\right]\right)$$
$$+ \sum_{i\in\mathcal{I}} \nu_i(t)\left(\delta_i a_i(t) - x_i(t)\right) + \sum_{i\in\mathcal{I}} \lambda_i(t)\left(\bar{a}_i - a_i(t)\right), \tag{A.4}$$

The remaining first order conditions for the costate variables are given by

$$\frac{\partial\mathcal{H}}{\partial\psi_j(t)} = -\phi_j(t) = -\dot{\mu}_j(t) + r\mu_j(t), \qquad \text{for } j \in \{V,N\} \tag{A.5}$$
$$\frac{\partial\mathcal{H}}{\partial a_i(t)} = -\mu_j(t) + \delta_i c_i'(x_i(t)) - \lambda_i(t) = \frac{dc_i'(x_i(t))}{dt} - rc'(x_i(t)),$$
$$\text{for } j \in \{V,N\} \text{ and } i \in j, \tag{A.6}$$

where we have used the fact that $|\nu_i(t)| = c_i'(x_i(t))$ throughout and defined $\dot{} := d/dt$. Note that (A.5) provides the dynamics of the shadow value of emissions reductions, given by $\mu_j(t)$, while (A.6) can be interpreted as the optimal path of marginal investment costs that minimizes the total cost of decarbonizing the economy subject to the cumulative emissions constraint.

We can use complementary slackness to simplify (A.5)–(A.6) before and after the decarbonization date T_i in each sector, as shown in the following two Lemmas.

Lemma A.1. *Consider* (2.4)*. For all $t < T_i$ with $i \in \mathcal{I}$, $\lambda_i(t) = 0$.*

Proof. Recall that the decarbonization date T_i is defined as $T_i := \inf\{t \in \mathbb{R}^+ : a_i(t) = \bar{a}_i\}$. It immediately follows that, prior to the decarbonization date, $\bar{a}_i - a_i(t) > 0$ by definition, implying that $\lambda_i(t) = 0$ for all $t < T_i$ by complementary slackness. □

Lemma A.2. *Consider* (2.4)*. For all $t < T_j^*$ where $j \in \{V,N\}$ and $T_j^* := \max\{T_k : k \in j\}$, $\phi_j(t) = 0$.*

Proof. Consider a set of sectors $j \in \{V,N\}$ and the maximum decarbonization time for that set of sectors $T_j^* := \max\{T_k : k \in j\}$. Given that $\psi_j(t=0) = 0$ and $\bar{a}_i - a_i(t) > 0$ for all $i \in j$ and $t < T_i$, $\dot{\psi}_j(t) > 0$ for all $t < T_j^*$. The constraint $\psi_j(t) \leq B_j$, where B_j is given by (2.2) for $j \in \{V,N\}$ binds at the time $T_j^* = \max\{T_j : j \in \{V,N\}\}$, i.e., when the last unit of emissions has been emitted before total decarbonization. Hence, for all $t < T_j^*$, $B_j - \psi_j(t) > 0$, and by complementary slackness, $\phi_j(t) = 0$ for $t < T_j^*$. □

Using Lemmas A.1 and A.2, the first order conditions for the costate variables become,

$$\dot{\mu}_j(t) = r\mu_j(t), \qquad \text{for } j \in \{V,N\} \tag{A.7}$$
$$(r+\delta_i)c_i'(x_i(t)) = \frac{dc_i'(x_i(t))}{dt} + \mu_j(t), \qquad \text{for } j \in \{V,N\} \text{ and } i \in j \tag{A.8}$$

for all $t < T_i$. Solving (A.7) implies the following path for the carbon price in the sector groupings $j \in \{C,N\}$ is given by

$$\mu_j(t) = \mu_j(0)e^{rt} = \mu_j e^{rt}, \tag{A.9}$$

where we have defined $\mu_j(t=0) \equiv \mu_j$ as the initial carbon price, which follows an exponentially increasing path, *á la* the Hotelling rule (Hotelling, 1931).[16] Using (A.9) in (A.8) and rearranging, we have

$$\frac{dc_i'(t)}{dt} - (r+\delta_i)c_i'(x_i(t)) = -\mu_j e^{rt} = \mu_j e^{rt}, \tag{A.10}$$

for each $j \in \{V, N\}$ and $i \in j$, where we have used the fact that μ_j is interpreted as a tax to change its sign. We can solve (A.10) using variation of parameters,

$$\begin{aligned} c_i'(x_i(t)) &= e^{(r+\delta_i)t}\left(C_x + \int_t^{T_i} (\mu_j e^{r\zeta})(e^{-(r+\delta_i)\zeta}) d\zeta\right), \\ &= e^{(r+\delta_i)t}\left[C_x + \frac{\mu_j}{\delta_i}\left(e^{-\delta_i t} - e^{-\delta_i T_i}\right)\right], \end{aligned} \tag{A.11}$$

where $C_x \in \mathbb{R}$ is a to-be-determined constant. Note we integrate from $t \to T_i$ as our boundary condition for investment – that in the steady state, $c_i(x_i(T_i)) = c_i(\delta_i \bar{a}_i)$ – occurs at the decarbonization time T_i. Using the aforementioned boundary condition, we can solve for C_x and write the final solution for the optimal marginal cost of investment as

$$c_i'(x_i(t)) = c'(\delta_i \bar{a}_i)e^{(r+\delta_i)(t-T_i)} + \frac{\mu_j}{\delta_i} e^{rt}\left(1 - e^{\delta_i(t-T_i)}\right). \tag{A.12}$$

In order to continue with an analytically tractable model for the remaining state variables, we must make the following assumption about investment costs.

Assumption 1. *The cost of investment takes a quadratic form,*

$$c_i(x_i(t)) = \frac{1}{2}\bar{c}_i x_i^2(t). \tag{A.13}$$

Using Assumption 1, we can solve (A.12) for the optimal investment path, $x_i^*(t)$ as

$$x_i^*(t) = \delta_i \bar{a}_i e^{(r+\delta_i)(t-T_i)} + \frac{\mu_j}{\bar{c}_i \delta_i} e^{rt}\left(1 - e^{\delta_i(t-T_i)}\right). \tag{A.14}$$

We can now use the optimal investment path (A.14) to solve for the optimal abatement path. Along the optimal path we have

$$\dot{a}_i^*(t) + \delta_i a_i^*(t) = x_i^*(t), \tag{A.15}$$

which can be solved using variation of parameters,

$$\begin{aligned} a_i^*(t) &= e^{-\delta_i t}\left(C_a + \int_0^t e^{\delta_i \zeta} x_i^*(\zeta) d\zeta\right) \\ &= e^{-\delta_i t}\left[\frac{\mu_j}{\bar{c}_i \delta_i}\left(\frac{e^{t(\delta_i+r)} - 1}{\delta_i + r} - \frac{e^{-\delta_i T_i}\left(e^{t(2\delta_i+r)} - 1\right)}{2\delta_i + r}\right) + C_a + \frac{\bar{a}_i \delta_i \left(e^{t(2\delta_i+r)} - 1\right) e^{-T_i(\delta_i+r)}}{2\delta_i + r}\right], \end{aligned} \tag{A.16}$$

with $C_a \in \mathbb{R}$ an undetermined constant. Using the boundary condition that $a_i(t=0) = 0$, we can solve

[16] In an abuse of notation, we have relabeled $t - t_0 \to t$, as the shift does not materially change the results if t is always defined as the first period when investment begins.

for C_a and write the optimal abatement path as

$$a_i^*(t) = e^{-\delta_i t}\left[\frac{\mu_j}{\bar{c}_i\delta_i}\left(\frac{e^{t(\delta_i+r)}-1}{\delta_i+r} - \frac{e^{-\delta_i T_i}\left(e^{t(2\delta_i+r)}-1\right)}{2\delta_i+r}\right) + \frac{\bar{a}_i\delta_i\left(e^{t(2\delta_i+r)}-1\right)e^{-T_i(\delta_i+r)}}{2\delta_i+r}\right]. \quad \text{(A.17)}$$

Finally, we can derive the optimal path of cumulative emissions. Noting that

$$\psi_j^*(t) - \psi_j(t=0) = \int_0^t \sum_{i\in j}\left(\bar{a}_i - a_i^*(\zeta)\right) d\zeta, \quad \text{(A.18)}$$

we can write

$$\psi_j^*(t) = \sum_{i\in j}\left(\mathcal{R}_i(t) - \mu_j \mathcal{B}_i(t)\right) \quad \text{(A.19)}$$

for each $j \in \{V, N\}$, with

$$\mathcal{R}_i(t) = t\bar{a}_i + \frac{r\bar{a}_i\left(e^{t\delta_i}-1\right)e^{-T_i(\delta_i+r)-t\delta_i}}{(\delta_i+r)(2\delta_i+r)} - \frac{\bar{a}_i\delta_i\left(e^{t(2\delta_i+r)}-2e^{t\delta_i}+1\right)e^{-T_i(\delta_i+r)-t\delta_i}}{(\delta_i+r)(2\delta_i+r)}, \quad \text{(A.20)}$$

$$\begin{aligned}\mathcal{B}_i(t) = {} & \frac{2\left(e^{rt}-1\right)}{r\bar{c}_i(\delta_i+r)(2\delta_i+r)} - \frac{r\left(e^{t\delta_i}-1\right)\left(e^{\delta_i T_i}-1\right)e^{-\delta_i(T_i+t)}}{\bar{c}_i\delta_i^2(\delta_i+r)(2\delta_i+r)} \\ & + \frac{e^{-\delta_i(t+T_i)}\left(-e^{t(2\delta_i+r)}+e^{\delta_i(T_i+t)+rt}+2e^{t\delta_i}-3e^{\delta_i(T_i+t)}+2e^{\delta_i T_i}-1\right)}{\bar{c}_i\delta_i(\delta_i+r)(2\delta_i+r)}.\end{aligned} \quad \text{(A.21)}$$

Evaluating sector's contribution to (A.19) at the decarbonization date of that sector yields an expression for the carbon price in that set of sectors in terms of the decarbonization dates,

$$\mu_j = \frac{\sum_{i\in j}\left(R_i(T_i) - B_i^*\right) + \sigma_j B_p}{\sum_{i\in j}\mathcal{B}_i(T_i)} \quad \text{(A.22)}$$

Combining (A.14), (A.17), and (A.19) results in the optimal solution to our model; the equivalent expressions for the non-challenged sectors are straightforward analogs. What remains is to determine numerical values for the decarbonization dates and the carbon price. We cannot hope to find solutions analytically, given the immense complexity of the equations involved. We therefore solve the following system of nonlinear, implicit equations for the carbon price and decarbonization dates,

$$\bar{a}_1 = a_1^*(t = T_1, \mu_j) \quad \text{(A.23)}$$

$$\vdots$$

$$\bar{a}_{|j|} = a_{|j|}^*(t = T_{|j|}, \mu_j) \quad \text{(A.24)}$$

$$\mu_j = \frac{\sigma_j B_p + \sum_{i\in j}\left(B_i^* - R_i(T_i)\right)}{\sum_{i\in j}\mathcal{B}_i(T_i)} \quad \text{(A.25)}$$

using a numerical root-finding algorithm. This completes the analytical solution to the model equations, see Table 5.

A final result is the following Lemma, showing the influence of exogenous technology change on the model.

Lemma A.3. *Consider (2.1) with an exogenous, economy-wide, constant technology growth rate given by $\varphi > 0$. This has the equivalent impact on policy as a shift in the social discount rate by φ.*

Table 5. Full Analytic Solutions of (2.4) Subject to Assumption 1 for Each Sector Set $j \in \{V, N\}$ and $i \in j$.

Variable	$t < T_i$	$t > T_i$
Investment	(A.14)	$\delta_i \bar{a}_i$
Abatement	(A.17)	$\bar{a}_i$
Cumulative emissions	(A.19)	$\sigma_j B_p + \sum_{i \in j} B_i^*$

Proof. Consider (2.1), and allow the technology-adjusted cost of investment in a sector $i \in I$ to be given by

$$C_i(x_i(t)) = e^{-\Phi_i(t)} c_i(x_i(t)) \tag{A.26}$$

where $\Phi_i(t)$ is the technology growth rate in the sector. If technology growth is exogenous, constant, and economy-wide, then $\Phi_i(t) = \varphi$, and can be assimilated into the discounting term in the objective function of (2.1), with the new discount rate

$$\tilde{r} := r + \varphi \tag{A.27}$$

as desired. □

B Proof of Cost Ranking of Policy Suites, Theorem 3.1

Here we provide a proof that the policy suites in Table 1 are nested, with the immediate heterogeneous option being the least expensive sub-optimal policy, the delayed economy-wide action option being the most expensive, and the delayed heterogeneous option being in-between these two.

Forerunners. Consider (2.1) and (2.4). We first note the signs of each of the following partial derivatives:

$$\frac{\partial c_i}{\partial x_i} > 0, \tag{B.1}$$
$$\frac{\partial x_i}{\partial \mu_j} > 0, \tag{B.2}$$
$$\frac{\partial T_i}{\partial \mu_j} < 0, \tag{B.3}$$
$$\frac{\partial x_i}{\partial T_i} < 0, \tag{B.4}$$

where (B.1) follows from the definition of convexity, (B.2) follows from (A.14), (B.3) simply states that higher carbon prices result in a more rapid decarbonization, and (B.4) follows from (A.14). The main equation we need to consider the following, which represents the aggregate policy costs, given by

$$\mathcal{C} = \int_0^\infty e^{-rt'} \sum_{j\in\{V,N\}} \left(\sum_{i\in j} c_i \left[x_i(t', T_i(\mu_j), \mu_j) \right] \right) dt'. \tag{B.5}$$

Note if $V = \emptyset$ and $\mu_j = \mu$ where μ is the optimal carbon price, (B.5) is the optimal cost, which we denote as $\mathcal{C}_{opt}$. Now, to the theorem.

Proof of Theorem 3.1. Consider (2.1) and (2.4). Assume that there are V politically vocal sectors facing a carbon price μ_V and a set of non-challenged sectors, N, facing a carbon price μ_N, such that the decarbonization of the challenged sectors is delayed by some amount $\delta T > 0$. One key inequality to note is that

$$\frac{\partial \mu_N}{\partial \mu_V} \leq 0 \tag{B.6}$$

which follows from the fact that decreasing the carbon price in the politically vocal sectors is a result of allocating a premium amount of emissions to these sectors, which lowers the emissions cap in the non-vocal sectors and raises the carbon price in the non-vocal sectors. We will prove the theorem via a perturbative approach. Throughout, let μ be the optimal carbon price.

Economy-wide delay. In an economy-wide delay strategy, we are effectively perturbing the economy-wide carbon price $\mu \to \mu + \delta\mu$ where $0 < \delta\mu \ll 1$ by infinitesimally shrinking our pollution quota, driving up the shadow value of abatement infinitesimally. If $\mathcal{C}_{econ-wide}$ is the aggregate policy cost associated with policy suite 4, we can write

$$\mathcal{C}_{econ-wide} = \int_0^\infty e^{-rt'} \sum_{i\in I} c_i \left[x_i(t', T_i(\mu+\delta\mu), \mu+\delta\mu) \right] dt'. \tag{B.7}$$

Taylor expanding (B.7) around $\delta\mu = 0$ gives us

$$\mathcal{C}_{econ-wide} = C_{opt} + \delta\mu \int_0^\infty e^{-\rho t'} \left(\sum_{i\in I} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu} \frac{\partial x_i}{\partial T_i} \right) \right] \right) dt' + \mathcal{O}\left((\delta\mu)^2 \right). \tag{B.8}$$

Immediate or delayed heterogeneous decarbonization. For the immediate or delayed heterogeneous strategy, we are, in effect, infinitesimally decreasing the challenged sectors' carbon price relative to the optimal price, $\mu_V = \mu - \delta\mu_V$ where $0 < \delta\mu_V \ll 1$, while also infinitesimally increasing the non-challenged sectors carbon price relative to the optimal by

$$\mu_N = \mu - \frac{\partial \mu_N}{\partial \mu_V} \delta\mu_V. \tag{B.9}$$

Note that (B.6) makes (B.9) positive, as expected. Using (B.5), we can write the total cost for the two policy suites, $\mathcal{C}_{relax}$ and $\mathcal{C}_{sec-delay}$, respectively, such that

$$\mathcal{C}_{relax/sec-delay} = \int_0^\infty e^{-rt'} \Bigg(\sum_{i\in V} c_i \left[x_i(t', T_i(\mu - \delta\mu_V), \mu - \delta\mu_V)\right] + \sum_{i\in N} c_i \left[x_i\left(t', T_i \left(\mu - \frac{\partial \mu_N}{\partial \mu_V}\delta\mu_V\right), \mu - \frac{\partial \mu_N}{\partial \mu_V}\delta\mu_V\right)\right] \Bigg) dt'. \tag{B.10}$$

We again Taylor expand (B.10) around $\delta\mu_V = 0$ to write

$$\mathcal{C}_{relax/sec-delay} = C_{opt} - \delta\mu_V \Bigg(\int_0^\infty e^{-\rho t'} \frac{\partial \mu_N}{\partial \mu_V} \left(\sum_{i\in N} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu}\frac{\partial x_i}{\partial T_i} \right)\right]\right) dt' + \int_0^\infty e^{-\rho t'} \left(\sum_{i\in V} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu}\frac{\partial x_i}{\partial T_i} \right)\right]\right) dt' \Bigg) + \mathcal{O}\left((\delta\mu_V)^2\right) \tag{B.11}$$

Synthesis. Consider the delayed heterogeneous and delayed economy-wide policies. Neglecting higher order terms and taking the difference between (B.8) and (B.11) and dividing by the change in carbon price,[17] we find

$$\begin{aligned} \frac{\mathcal{C}_{econ-wide} - \mathcal{C}_{sec-delay}}{\delta\mu} &= \left(1 + \left.\frac{\partial \mu_N}{\partial \mu_V}\right|_{sec-delay}\right) \int_0^\infty e^{-\rho t'} \left(\sum_{i\in N} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu}\frac{\partial x_i}{\partial T_i} \right)\right]\right) dt' \\ &= \left(1 - \left|\frac{\partial \mu_N}{\partial \mu_V}\right|_{sec-delay}\right) \underbrace{\int_0^\infty e^{-\rho t'} \left(\sum_{i\in N} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu}\frac{\partial x_i}{\partial T_i} \right)\right]\right) dt'}_{=:\mathcal{A}} \end{aligned} \tag{B.12}$$

where we have canceled out the contribution to the change in costs owing to the challenged sectors, C and used (B.6). All that remains to prove the Proposition is to verify that $\mathcal{A}$ is positive. Using (B.1)-(B.4), we see that every individual term in $\mathcal{A}$ is positive, ensuring that $\mathcal{A}$ is positive. Therefore, we have

$$\mathcal{C}_{econ-wide} > \mathcal{C}_{sec-delay} \tag{B.13}$$

proving that delaying all decarbonization policies is always more expensive than delaying sectoral policies.

Carrying out the same procedure for the immediate and delayed heterogeneous policies, we have

$$\begin{aligned} \frac{\mathcal{C}_{sec-delay} - \mathcal{C}_{relax}}{\delta\mu} &= \left(- \left.\frac{\partial \mu_N}{\partial \mu_V}\right|_{sec-delay} + \left.\frac{\partial \mu_N}{\partial \mu_V}\right|_{relax}\right) \int_0^\infty e^{-\rho t'} \left(\sum_{i\in N} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu}\frac{\partial x_i}{\partial T_i} \right)\right]\right) dt' \\ &= \left(\left|\frac{\partial \mu_N}{\partial \mu_V}\right|_{sec-delay} - \left|\frac{\partial \mu_N}{\partial \mu_V}\right|_{relax}\right) \int_0^\infty e^{-\rho t'} \left(\sum_{i\in N} \left[\frac{\partial c_i}{\partial x_i} \left(\frac{\partial x_i}{\partial \mu} + \frac{\partial T_i}{\partial \mu}\frac{\partial x_i}{\partial T_i} \right)\right]\right) dt'. \end{aligned} \tag{B.14}$$

[17] In an abuse of notation, we relabel $\delta\mu_V \equiv \delta\mu$, as $\delta\mu$ and $\delta\mu_V$ are equivalent between the settings we consider (they represent the departure from the optimal carbon price for sectors facing higher carbon prices relative to the optimal).

Therefore, the sign of (B.14) depends on the relative magnitudes of the change in the non-challenged carbon price owing to a distortion in the challenged sector carbon price between each policy suite.

Considering (A.22), in order for the change in the carbon price in the immediate heterogeneous policy to be less than that of the delayed heterogeneous policy for an equivalent amount of delay, $B_{p,relax} < B_{p,sec-delay}$. It can readily be seen that this condition is always satisfied; the emissions premium for the delayed heterogeneous policy, $B_{p,sec-delay}$ can be seen as an upper bound on emissions premiums for the immediate heterogeneous action policy. For example, if the emissions premiums were equal (i.e., $B_{p,relax} = B_{p,sec-delay}$), then in the case of immediate heterogeneous policy, some amount of investment would happen immediately, and relative to the delayed heterogeneous policy, the challenged sectors would be decarbonized marginally later as investment is smoothed out over time. Therefore, for equivalent amounts of delay (as we are considering here), it must be that $B_{p,relax} < B_{p,sec-delay}$, otherwise the assumption of equivalent amounts of delay for each policy suite would be violated.

Hence, we have

$$\left(\left| \frac{\partial \mu_N}{\partial \mu_V} \right|_{sec-delay} - \left| \frac{\partial \mu_N}{\partial \mu_V} \right|_{relax} \right) > 0 \tag{B.15}$$

and by (B.14) we have

$$\mathcal{C}_{sec-delay} > \mathcal{C}_{relax}. \tag{B.16}$$

Therefore, it must be the case that

$$\mathcal{C}_{econ-wide} > \mathcal{C}_{sec-delay} > \mathcal{C}_{relax}, \tag{B.17}$$

as desired. □

C Determining Emissions Premiums for the Immediate Heterogeneous Policy

We now provide an algorithm for determining how much emissions premium, B_p, is required to delay a sector's decarbonization date, T_i, by some number of years, δT_i. For simplicity, consider one vocal sector, such that $|V| = 1$. The system (A.23)–(A.25) can be formulated as a constraint to an additional root-finding algorithm, such that

$$\min_{B_p} \left[T(B_p) - T^* - \delta T \right], \tag{C.1}$$

$$\text{Subject to} : T(B_p) - T^* - \delta T > 0, \tag{C.2}$$

$$T(B_p) = \arg\min_{T_1} \left[\vec{f}(T_1, \mu_V; B_p) = \vec{0} \right], \tag{C.3}$$

where (C.2) ensures we always get a positive $T(B_p)$, T^* is the decarbonization date in the optimal case (i.e., without political constraints), δT is the delay amount, and

$$\vec{f}(T_1, \mu_V; B_p) = \begin{pmatrix} \bar{a}_1 - a_1^*(T_1, \mu_V) \\ \mu_V - \dfrac{B_p + B_1^* - R_1(T_1)}{\mathcal{B}_1(T_1)} \end{pmatrix}. \tag{C.4}$$

In words, the approach is to specify some B_p, and solve (A.23)–(A.25) using a root-finder. This yields the decarbonization date of the vocal sector, $T(B_p)$; comparison with this decarbonization date and the target date $T^* + \delta T$ informs the next B_p choice. Carrying out this process iteratively results in a B_p such that the new decarbonization date in the vocal sector, $T(B_p)$ is exactly equal to $T + \delta T$, as desired.

D Calibration of Numerical Experiments

The remaining carbon budget. We use estimates from Friedlingstein et al. (2023) for the remaining carbon budget associated with a 1.7 °C temperature target.

Social discount rate. We set the social discount rate to 2% yr^{-1}, in line with a recent international expert elicitation Drupp et al. (2018) and the US EPA's prevailing rate for their social cost of carbon estimates (National Center for Energy Economics, 2022).

Sectoral parameters. We lift the values of emissions intensities, marginal investment costs, and capital depreciation rates from Bauer et al. (2025), see their 1.7 °C scenario, the "low cost, linear" calibration. Note that marginal investment costs are treated as constant in time, abstracting from the variable and fixed components of abatement costs (Gillingham and Stock, 2018), and are calibrated to the net lifetime cost of each abatement option in Intergovernmental Panel on Climate Change (2022).

Emissions scenario. We assume that, without abatement investments, emissions will remain at their current levels in each sector, which would amount to about ∼40 $GtCO_2$ yr^{-1} of emissions. This level of emissions is approximately equal to the peak emissions of SSP2–4.5 (the "middle of the road" emissions scenario used by the IPCC (Intergovernmental Panel on Climate Change, 2021)) and the Resources for the Future-socioeconomic projections used in the United States' Environmental Protection Agency's estimates of the social cost of carbon (Riahi et al., 2017; National Center for Energy Economics, 2022). Indeed, in each of these baselines, emissions are expected to rise to just above 40 $GtCO_2$ yr^{-1} before declining. This assumption relies in part on Wright's law, which leads to declining energy intensity to offset growth effects on total emissions, as is the case in SSP2 (see Figure 1 in Fricko et al., 2017).

There are a few caveats to this approach. The first caveat is that some green technologies are already cost-competitive with their dirty equivalents, and therefore do not necessarily require a carbon price to be assimilated into the economy. These "costless" abatement technologies are a main source of uncertainty in projecting the costs of the green transition (Kotchen et al., 2023). Therefore, our assumption that emissions will remain at peak levels without a carbon price can be viewed as conservative, as all abatement in our approach is spurred by the presence of a carbon price.

The second caveat is that we are assuming that the relative sectoral levels of emissions are held constant (in addition to total aggregate levels of emissions) without investments in abatement capital. While there is some variation in the relative level of emissions between sectors in SSP2–4.5 over time (see Figure S6 in the *Supplementary Information*), the primary change in the relative emissions rates comes from decarbonizing the energy sector and the agriculture, forestry and other land use sector (AFOLU) becoming a net carbon sink (via, *e.g.,* reforestation). These changes, however, are driven by assumptions about policy and behavioral changes within the MESSAGE-GLOBIUM model that generates SSP2–4.5 emissions time series (Riahi et al., 2017); in our model, these emissions changes would have to be induced by investments in abatement capital stocks. The remaining sectors contribute marginal changes in the total emissions shares, with aviation accounting for the largest increase in its contribution (2100 levels of aviation emissions are 100% higher than 2020 levels). However, most changes are small relative to total emissions, other than the decline in energy and AFOLU emissions. This gives us confidence that we can use 2025 emissions levels as representing a sector's emissions intensity over the entire policy period, given that the relative levels are roughly constant over time in SSP2–4.5.

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Supplemental Information for: "Optimal Allocation of Abatement Effort under Political Constraints: The Economic Cost of Delaying Sectoral and Economy-wide Climate Policies"

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Table S1. Intergovernmental Panel on Climate Change Working Group 3 Mitigation Options by Sector. Mitigation options are taken from Intergovernmental Panel on Climate Change (2022), Figure SPM.7 in the Summary for Policymakers.

Sector	Options
Energy	Wind energy
	Solar energy
	Bioelectricity
	Hydropower
	Geothermal energy
	Nuclear energy
	Carbon capture and storage (CCS)
	Bioelectricity with CCS
	Reduce methane emissions from coal mining
	Reduce methane emissions from oil and gas
Industry	Reduction of non-CO_2 emissions

Continued on the next page

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Sector	Options
	Cementious material substitution
	Carbon capture with utilization and storage
	Feedstock decarbonization, process change
	Fuel switching (electr, nat. gas, bio-energy, H_2)
	Enhanced recycling
	Material efficiency
	Energy efficiency
Agriculture	Reduce methane and CO_2 emissions in agriculture
	Carbon sequestration in agriculture
Transport	Aviation - energy efficiency
	Shipping - efficiency and optimization
	Electric heavy duty vehicles
	Fuel efficiency heavy duty vechiles
	Shift to bikes and e-bikes
	Shift to public transportation
	Electric light duty vehicles
	Fuel efficiency light duty vehicles
Buildings	Enhanced use of wood products
	Improvement of existing building stock
	Onsite renewable production and use
	New buildings with high energy performance
	Efficient lighting, appliances and equipment
	Avoid demand for energy services
Waste	Reduce methane emissions from wastewater
	Reduce methane emissions from solid waste
Forestry	Shift to sustainable healthy diets
	Reduce food loss and food waste
	Forest management, fire management
	Restoration (e.g., reforestation)
	Reduce conversion of natural ecosystems

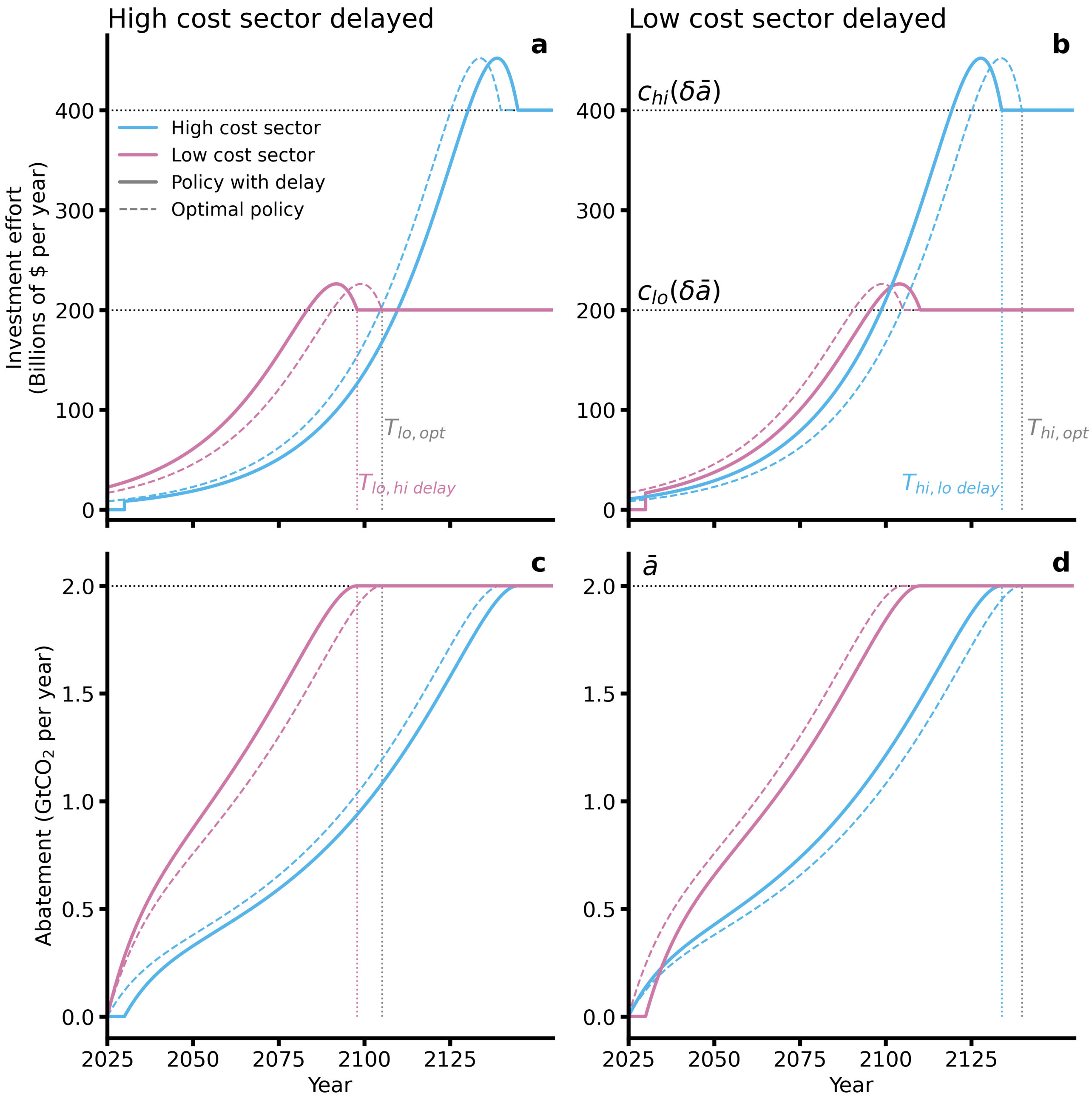

Figure S1. Two Sector Example of Model Behavior with Different Marginal Investment Costs. Panel **a** shows the optimal investment effort, $c(x)$, for both sectors in the optimal policy (dashed lines) and in the policy where the decarbonization of the high cost sector is delayed by five years (solid lines). The high cost sector investment path is in blue, while the low cost sector is in pink. The black dotted lines show the steady state investment effort for both sectors (see the labels in panel **b**). Panel **b** is as **a**, but when decarbonizing the low cost sector is delayed by five years. Panel **c** and **d** show the optimal abatement in each policy case. The black dotted line in panels **c** and **d** show the steady state abatement rate.

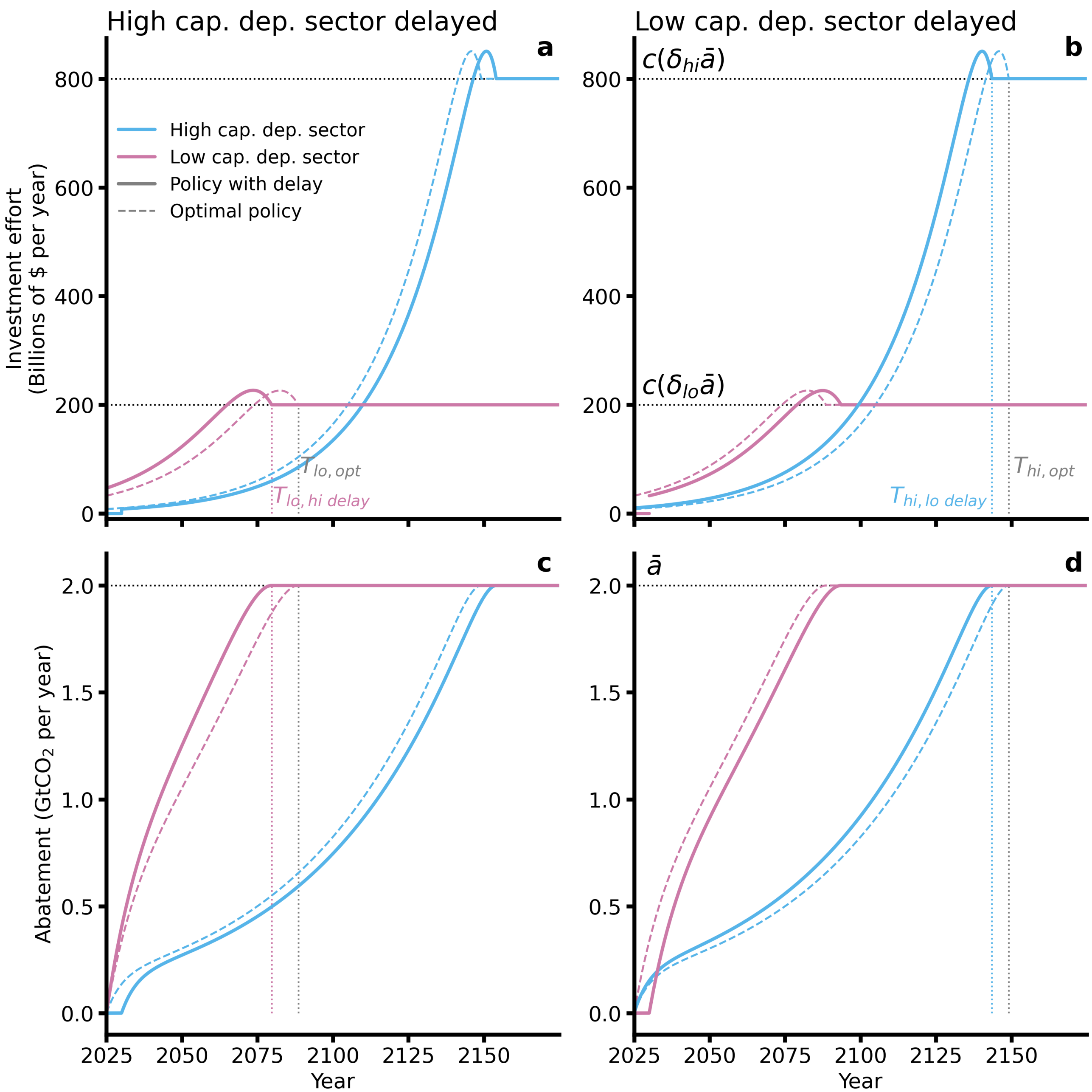

Figure S2. Two Sector Example of Model Behavior with Different Capital Depreciation Rates. Panel **a** shows the optimal investment effort, $c(x)$, for both sectors in the optimal policy (dashed lines) and in the policy where the decarbonization of the high capital depreciation rate (abbreviated to "cap. dep." in the figure to save space) sector is delayed by five years (solid lines). The high capital depreciation rate sector investment path is in blue, while the low capital depreciation rate sector is in pink. The black dotted lines show the steady state investment effort for both sectors (see the labels in panel **b**). Panel **b** is as **a**, but when decarbonizing the low capital depreciation rate sector is delayed by five years. Panel **c** and **d** show the optimal abatement in each policy case. The black dotted line in panels **c** and **d** show the steady state abatement rate.

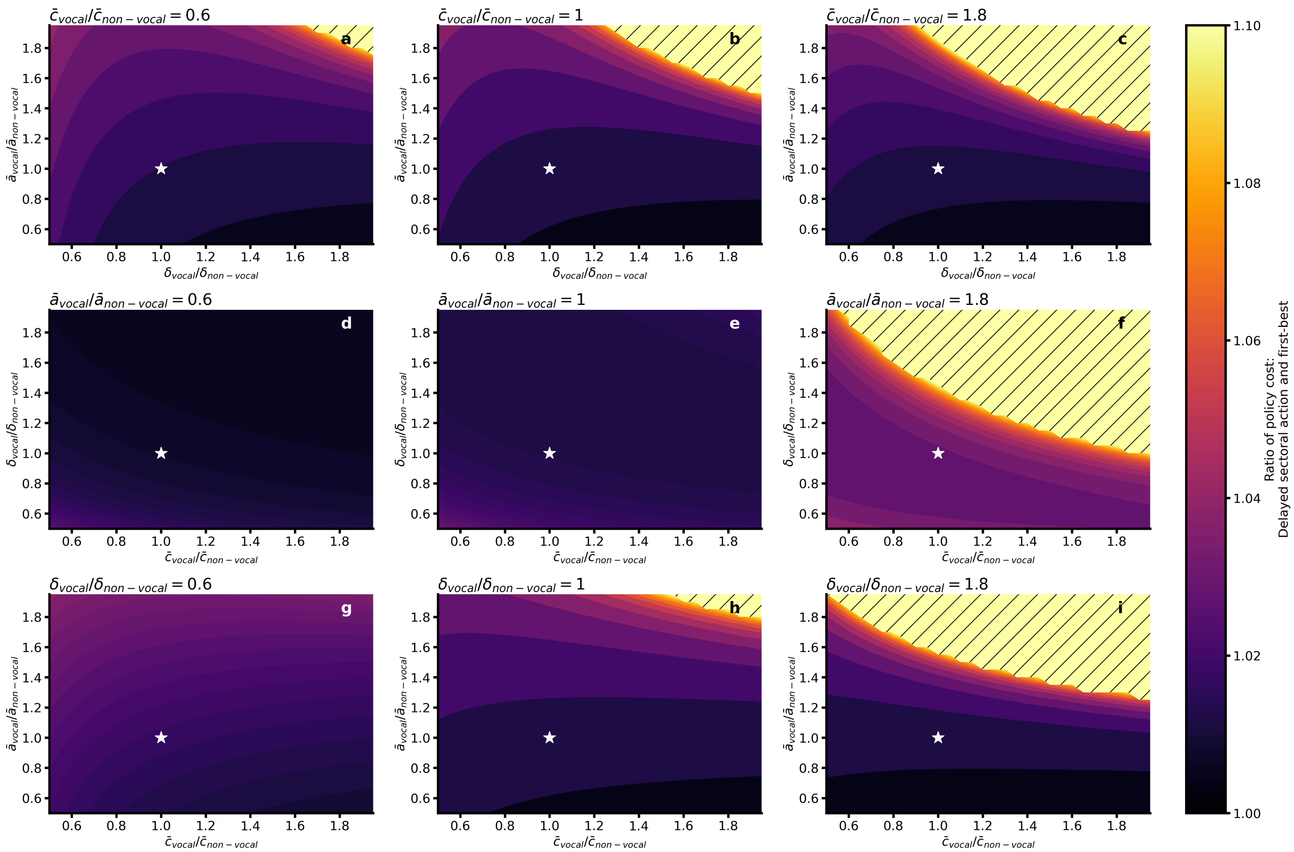

Figure S3. Sensitivity of Policy Cost to Different Sectoral Configurations, Grid of Heatmaps. Panels **a–c** are heatmaps of total policy cost sensitivity to co-varying the emissions intensity and capital depreciation rate of the vocal sector, holding marginal investment costs fixed. Panels **d–f** are as **a–c** but hold the relative emissions intensity of the vocal and non-vocal sectors constant. Panels **g–i** are as **a–c** but hold the relative capital deprecation rates between the vocal and non-vocal sectors constant. Notice that in all cases, most of the variability can be attributed to the emissions intensity of the vocal sector being larger than the non-vocal sector. See the titles at the top of each panel for the relative values of the parameters being held fixed. Hatching represents infeasible parameter combinations (because delaying climate policies causes the carbon budget allocated to the non-vocal sectors to be zero or negative). The white stars show the points where sectors have the same values for the parameters that are being covaried.

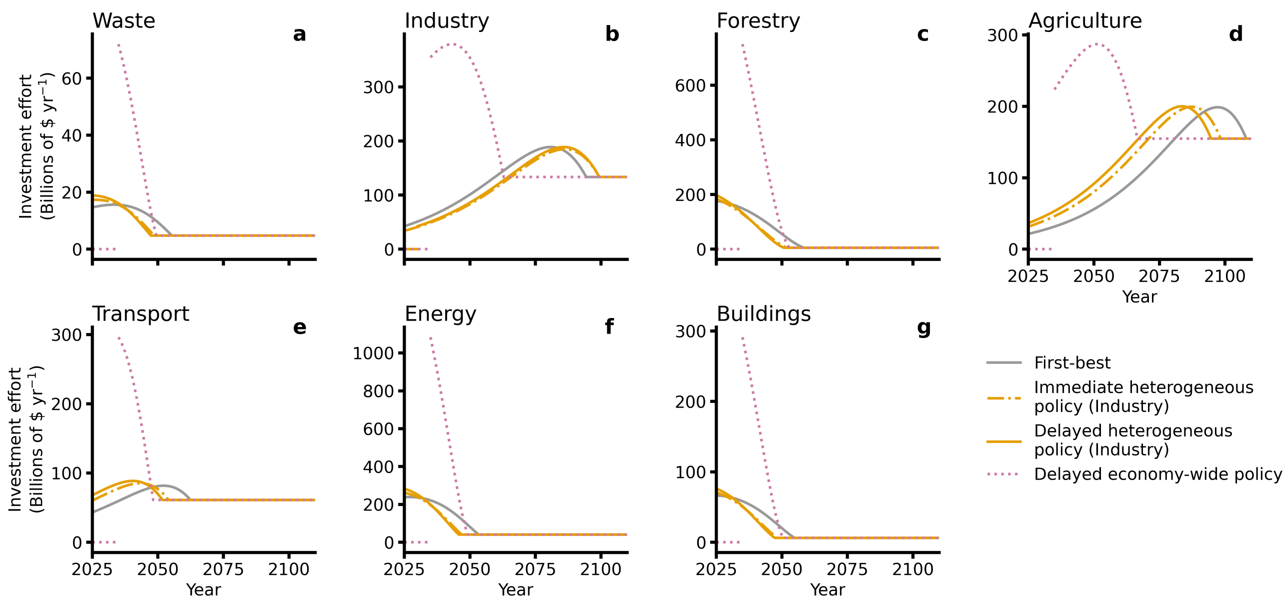

Figure S4. Investment Paths when Industry is Delayed. Panels show the optimal investment path in each sector when industry is treated as the politically vocal sector. The first-best path is given by the solid, grey lines; the immediate heterogeneous path is given by the orange dash-dot lines; the delayed heterogeneous path is given by the orange solid lines; and the delayed economy-wide path is given by the pink dotted line.

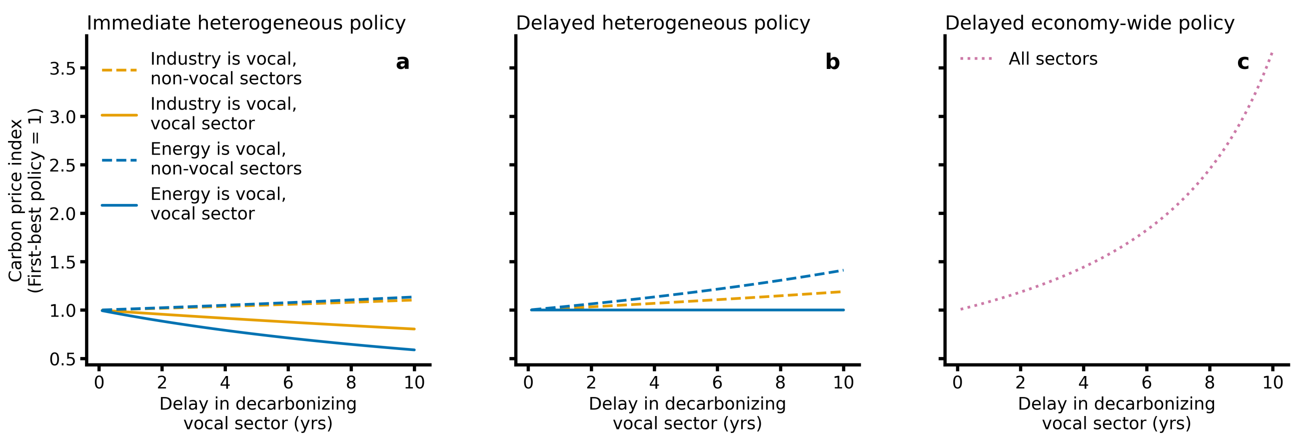

Figure S5. Carbon Prices. Panel **a** shows the carbon price facing the politically vocal sector relative to the first-best carbon price (solid lines) and the carbon price facing non-vocal sectors relative to the first-best carbon price (dashed lines) in the immediate heterogeneous action policy. Orange lines show results when industry is the vocal sector, while the blue lines show results when energy is politically vocal. Panel **b** is as panel **a** but for the delayed heterogeneous action option. Panel **c** shows the carbon price facing the entire economy relative to the first-best when economy-wide climate action is delayed.

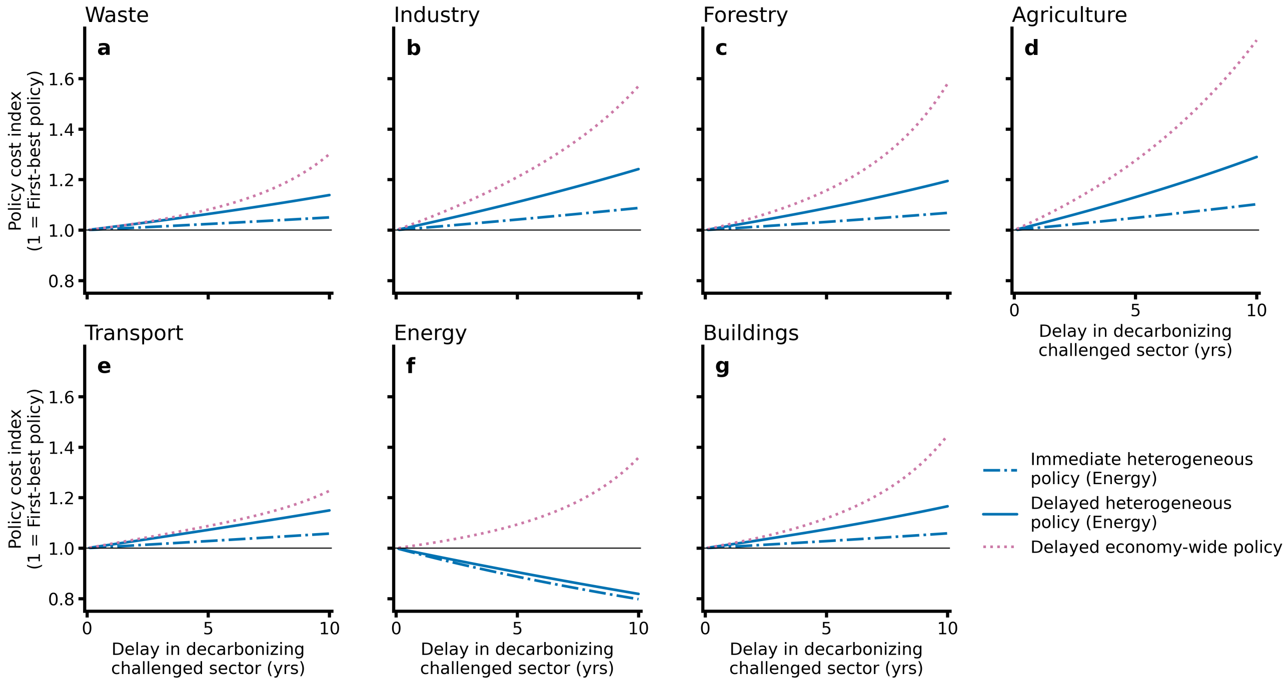

Figure S6. Relative Cost of Policy Suites Broken Down by Sector. Shown is the relative cost of policy (1 = first-best) for the immediate heterogeneous (blue dash-dot lines), delayed heterogeneous (blue solid lines), and delayed economy-wide (pink dotted) policies when energy is the politically vocal sector.

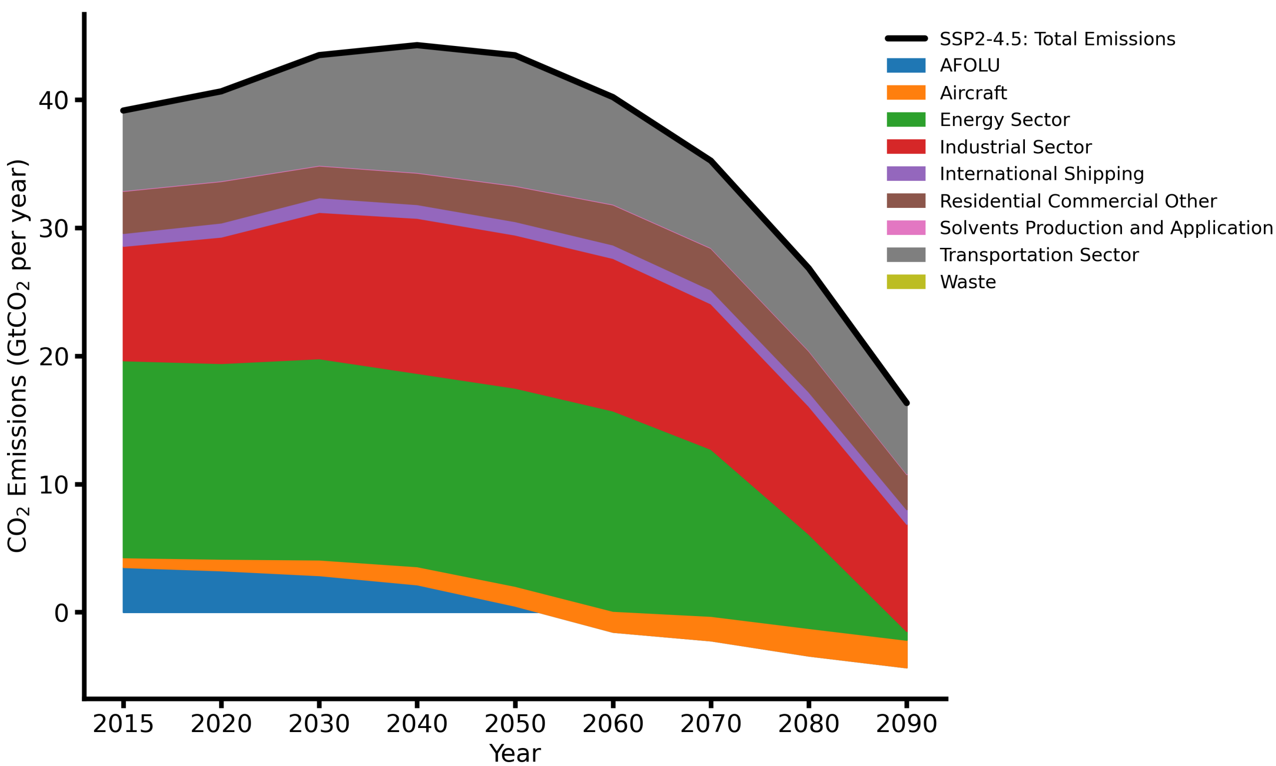

Figure S7. Relative Total Emissions Between Sectors in SSP2–4.5 Scenario. Note the AFOLU sector represents emissions from agriculture, forestry and other land use changes and becomes a net emissions sink by mid-century.

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