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Trade-offs in climate policy: Combining low-carbon standards with modest carbon pricing

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Abstract

To design climate policy decision makers must choose from a variety of policy options such as carbon pricing and low-carbon standards. Past research suggests that choosing between these approaches involves trade-offs between the relative efficiency and progressivity of carbon pricing on the one hand and the political acceptability of standards on the other. We argue that a climate policy portfolio that combines both approaches may balance the distinct advantages of each, as well as provide opportunity for consensus between advocates of either option. This paper compares the efficiency of different combinations of standards and carbon pricing by extending previous theory and performing novel experiments using two energy system models. Consistent with prior work, combining low-carbon standards and carbon pricing is shown to reduce policy cost relative to relying on standards alone. More importantly, we find that this cost-saving benefit diminishes with the extent to which the policy portfolio relies on carbon pricing. This suggests that, by adopting modest carbon pricing, policy makers would accomplish a disproportionately large share of the cost savings of economically optimal carbon pricing.

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1 Introduction

Climate policy makers have an array of policy options to choose from to meet CO_2 emission targets. The economics literature agrees that least-cost climate policy would primarily[1] feature carbon pricing, in the form of taxes or cap-and-trade (Pigou (1932); Stern (2006); Stavins (2008)). However, implementation efforts have shown such policies to be politically unpopular (Rabe (2018); Jenkins (2014)), certainly at pricing levels recommended by economic theory. Political constraints, if binding, may justify other, "second-best" policies from both economic efficiency and public choice theory perspectives, either because carbon pricing does not exist or because the level of the carbon price is below the efficient level (Lipsey and Lancaster (1956); Wagner (2015); Meckling and Kelsey (2015); Tvinnereim and Mehling (2018)). Alternative CO_2-reducing policies such as low-carbon technology subsidies and standards have seen relatively wide implementation[2].

Standards, which mandate a given low-carbon technology share, are a particularly common form of climate policy. Such policies are employed across U.S. states in the electricity and transportation sectors. Examples include Renewable Portfolio Standards (RPS), transportation fuel standards, and more recent zero-emission vehicle standards. At the federal level, such policies include the Corporate Average Fuel Economy (CAFE) standard and the Renewable Fuel Standard. Recently, Clean Energy Standards (CES) have come to occupy a central position in debates about future climate policy (House Select Committee on the Climate Crisis (2020); House Committee on Energy and Commerce (2020)). Recent national polling showed such policies to be relatively popular compared to alternative approaches (Bergquist, Mildenberger, and Stokes (2020)).

While standards have political feasibility advantages relative to carbon pricing, they have been shown to be less economically efficient (Goulder and Parry (2008); Holland, Hughes, and Knittel (2009); Knittel and Sandler (2011))[3] and to impose higher economic costs on low-income households (Davis and Knittel (2016); Cronin, Fullerton, and Sexton (2017); Goulder

[1] Other policies are also generally seen as necessary components of an optimal climate policy portfolio to correct for additional market failures that contribute to climate change such as knowledge spillovers that delay the diffusion of clean technologies (Stern (2006); Borenstein (2012); Lehmann and Gawel (2013); Jaffe, Newell, and Stavins (2005); Kalkuhl, Edenhofer, and Lessmann (2012)).

[2] In this paper, we think of such policies as climate policy instruments even though they are frequently motivated by rationales other than climate change mitigation, such as economic development (Borenstein (2012); Gawel, Strunz, and Lehmann (2014)). Such non-climate impacts may be considered among the factors explaining their political popularity.

[3] In addition to studies showing carbon pricing reduces emissions at a lower cost than standards, recent research found that carbon pricing results in greater air pollution co-benefits for every ton of CO2 abated relative to RPSs (Dimanchev et al. (2019)).

et al. (2019)). Therefore, the choice between carbon pricing and standards involves a trade-off between the relative efficiency and progressivity of carbon pricing on the one hand and the assumed political acceptability advantages of standards on the other. A balance between these competing considerations may be achieved through a certain combination of both policy options (Goulder and Parry (2008)). However, most previous research has compared the two policies in isolation, comparing the efficiency of a climate policy exclusively comprising one type of policy to a climate policy exclusively comprising the other type. Some authors have explored the efficiency of a combination of carbon pricing and second-best policy but only considered a single pre-defined combination of these policies (Bertram et al. (2015); Rausch and Karplus (2014); Singh, Winchester, and Karplus (2019); Kalkuhl, Edenhofer, and Lessmann (2013)).

In this paper, we compare different combinations of standards and carbon pricing. We frame climate policy making as a choice among alternative policy portfolios that reduce the same amount of CO_2 but differ with respect to how much they rely[4] on standards or carbon pricing. These alternative policy portfolios can be imagined on a spectrum between standards-only and pricing-only policy, with varying reliance on each type of policy in between (illustrated in Figure 1).

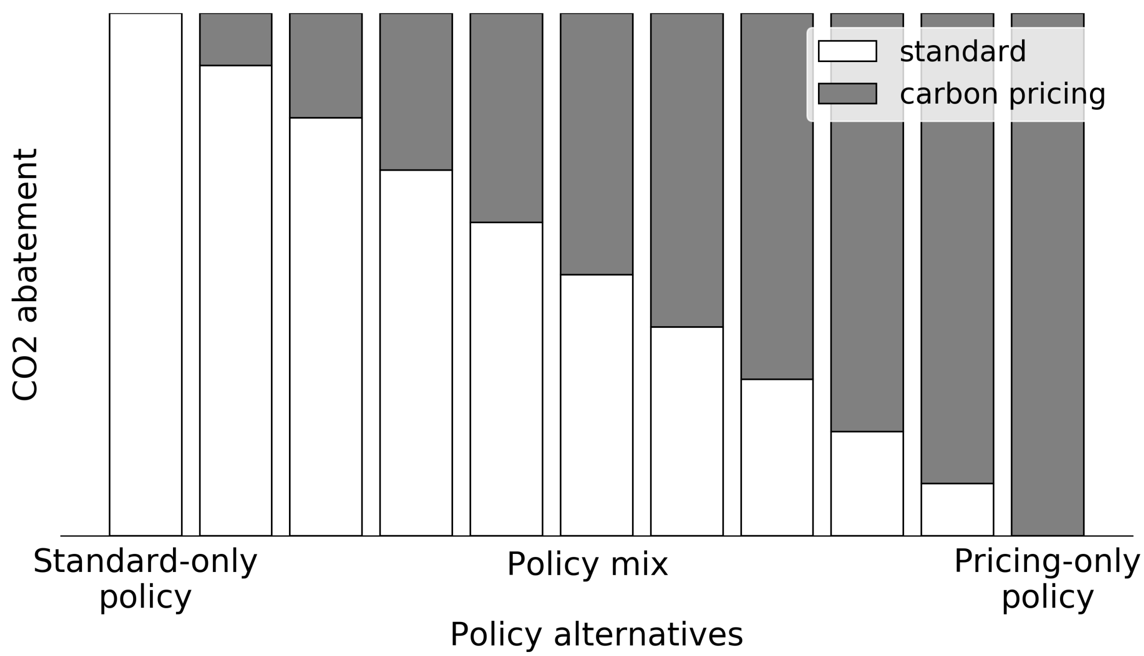

Figure 1: Indicative spectrum of policy portfolio alternatives

[4] "Reliance" can be defined in multiple ways. We show how policy costs vary with 1) the relaxation of the stringency of the standard under a CO_2 cap; and 2) the share of abatement caused by each policy type.

A climate policy portfolio that includes carbon pricing, in addition to a standard, is expected to cost less than a pure standard-based climate policy, as found in previous literature. We define this decreases in policy cost (or increase in welfare) as the efficiency benefit of carbon pricing. To inform the choice of a policy portfolio, we explore how this efficiency benefit varies as the policy portfolio relies more or less on each policy. In other words, we investigate the marginal benefit of carbon pricing across different policy portfolios.

We approach these questions in two ways. First, in section 2, we introduce a theoretical framework for comparing the efficiencies of policy portfolios. Second, in section 3, we use a novel experimental design to quantify the costs of different policy portfolios using the energy system models EPPA and GenX.

Our main finding is that the efficiency benefit of carbon pricing exhibits diminishing marginal returns. This suggests that carbon pricing follows the Pareto principle (Pareto (1906)): some carbon pricing delivers a disproportionately large share of the benefits of optimal pricing-only policy. In section 4, we discuss implications for future policy. We conclude that modest carbon pricing would play a valuable role in climate policy by reducing total policy costs relative to a policy that relies on standards alone and provide revenues to undo the regressive nature of standards.

2 Theoretical model

To represent the choice between different policy combinations of standards and carbon pricing, we extend the framework of Holland, Hughes, and Knittel (2009). We consider an economy with two products: a high-carbon product (for example, electricity generated from coal) with quantity of production denoted as q_H, and a low-carbon product (for example, electricity generated from renewables): q_L. The two products have emission intensities β_H and β_L such that $\beta_H > \beta_L$ (we also show that our findings hold in the case where the low-carbon product has no emissions). The cost of production for each products is represented by a cost function with increasing marginal cost $C_H(q_H)$ and $C_L(q_L)$ such that $C_i(q_i)' > 0$ and $C_i(q_i)'' > 0$. The low-carbon product is assumed to be more expensive at all levels of production such that $C_L(q) > C_H(q)$. Society receives aggregate utility from consuming the two products expressed as a function $U(q_H, q_L) = U(q_H + q_L)$. The utility function is assumed to be such that the two products are perfect substitutes, with non-increasing returns to scale. The state of the economy will be represented by the optimal solution to the welfare maximization problem expressed below. We denote the resulting welfare W^*.

$$\max_{q_H, q_L} W = U(q_H, q_L) - C_H(q_H) - C_L(q_L)$$

If the policy maker wishes to increase the share of the low-carbon product, a low-carbon standard, such as a Renewable Portfolio or Clean Energy Standard, can be introduced, expressed as the constraint: $\frac{q_L}{(q_H+q_L)} \geq \sigma$. The new state of the economy would be represented by the solution to the welfare maximization problem subject to the low-carbon standard constraint.

Figure 2.a represents this optimization problem graphically, similarly to the representation in Holland, Hughes, and Knittel (2009). The expression for welfare, $U(q_H, q_L) - C_H(q_H) - C_L(q_L)$, is represented by indifference circles, with each circle representing a different level of welfare. The solid line represents the low-carbon product standard constraint, everywhere on this line the share of low-carbon energy is σ. Optimal welfare without policy, and ignoring the externality, is represented by point X. As shown by Holland, Hughes, and Knittel (2009), the equilibrium solution after the implementation of the standard is found at the tangency of the indifference curves and the technology standard constraint, represented by point A.

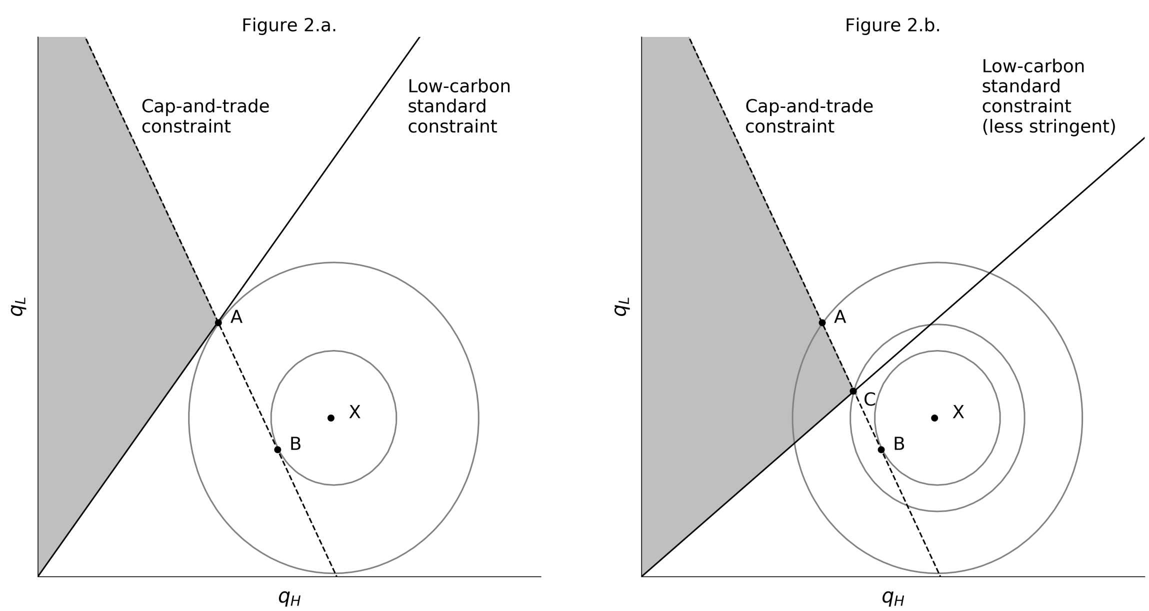

Figure 2: Welfare maximization with policy constraints for a low-carbon standard and a cap-and-trade
The grey shaded area represents the feasibility region of possible combinations of q_H and q_L.

The policy maker can also introduce a carbon pricing policy. We represent this as a constraint on CO_2 (reflecting a cap-and-trade policy):[5] $q_H\beta_H + q_L\beta_L \leq c$. This constraint is illustrated in Figure 2.a by the dashed line. If this is the only policy implemented, the new state of the economy would be represented by the solution to the welfare maximization problem subject to the cap constraint, which would occur at point B as shown in Holland, Hughes, and Knittel (2009). Note that we have illustrated the CO_2 cap such that it achieves the same level of CO_2 reductions as the standard (the dashed line crosses point A). This is true because A is on the cap-and-trade constraint line. The two policies can therefore be considered comparable. It can be confirmed visually that the cap-and-trade policy achieves the chosen emission reduction more efficiently than the standard as point B is associated with a higher indifference curve than point A. The level of optimal welfare under the cap-and-trade can be said to reflect optimal climate policy[6]. In this framework, carbon pricing is more efficient because it results in the optimal choice between the two products.

We extend this framework by allowing the policy makers to choose different combinations of both a standard and carbon pricing[7]. Consider a case where both constraints are implemented at once. The feasible region would be represented by the shaded area in Figure 2.a. Intuitively, the optimal solution where welfare is maximized will be found at the intersection of the two constraints. As drawn in Figure 2.a, this would be point A. At this point, all CO_2 reductions are being achieved by the standard. However, the policy maker can also choose to relax the standard, and allow the cap constraint to enforce emission reductions. This would increase reliance on the cap-and-trade policy and increase the carbon price. The new optimal solution will be a point between A and B along the dashed line representing the CO_2 constraint. As we move from A to B, we are progressively relying more on carbon pricing and less on the standard since we are relaxing the standard constraint. Together, all points on this line segment represent the spectrum of policy choices available (illustrated earlier in Figure 1).

Figure 2.b illustrates one possible policy mix. The new equilibrium is now at point C. The level of welfare resulting from the policy mix (represented by the circle going through point C) is not as high as under optimal climate policy (the circle going through point B) but it is closer to the optimal than the welfare achieved under the standard (the circle going through point A). This shows that a mix of the two policies results in a more efficient outcome (higher

[5]In this framework, a carbon tax and cap-and-trade are equivalent.

[6]assuming the chosen level of emission reduction, i.e. the reduction achieved by the standard, is the optimal level of abatement

[7]This framework directly represents a number of examples around the world where jurisdictions (such as Europe and California) have implemented a cap on emissions together with low-carbon standards on sectors that fall within the cap.

welfare, or, in other words, lower policy costs) than a pure standard-based policy. We term this improvement in welfare as the efficiency benefit of carbon pricing.

To choose between different policy mixes requires an understanding of how the welfare benefit of carbon pricing varies as the policy mix shifts from a standard toward carbon pricing (the primary research question of this paper) as well as the political costs associated with each policy (something we do not attempt to model). Figure 2.b suggests that these efficiency benefits exhibit diminishing marginal returns. Point C was chosen as the half-way reduction in the standard toward point B[8]. As can be observed from the figure, the welfare circle going through point C is more than half-way between the welfare circle going through point A and the optimal welfare circle going through point B. It can be observed in this figure that this non-linearity in the welfare improvement is caused by the curvature of the welfare circle. Note that this analysis assumes that welfare increases linearly with increased production (i.e. the utility function assumes constant returns to scale). In the following, we generalize our observations.

Two propositions emerge out of our graphical analysis, which we prove algebraically.

Proposition 1 *Welfare is weakly decreasing in sigma,* $\frac{\partial W^*}{\partial \sigma} \leq 0$. *That is, for a given level of pollution, provided the standard is binding, welfare decreases in how much society achieves that level through a standard, compared to carbon pricing. The inequality is strict when the standard constraint binds.*

Proposition 2 $\frac{\partial^2 W^*}{\partial \sigma^2} \leq 0$. *That is, welfare improvement from relying less and less on standards exhibits diminishing marginal returns. The inequality is strict when the standard constraint binds.*

To prove these, we derive $\frac{\partial W^*}{\partial \sigma}$ and $\frac{\partial^2 W^*}{\partial \sigma^2}$. We briefly describe the procedure here and refer to the detailed derivation in the Appendix.

To derive $\frac{\partial W^*}{\partial \sigma}$, we first observe that when both constraints bind, at W^* both constraints are just binding, or that the following system of equation holds:

$$\frac{q_L}{(q_H + q_L)} = \sigma$$

[8] if σ_{opt} is the standard going through point B and σ_1 is the standard going through point A, then the standard going through point C was chosen as $\sigma_2 = \sigma_1 - \frac{1}{2}(\sigma_1 - \sigma_{opt})$

$$q_H \beta_H + q_L \beta_L = c$$

We use these equations to express q_H and q_L in terms of σ, c, β_H, β_L. This allows us to express W^* as a function of the same parameters: $W(\sigma, c, \beta_H, \beta_L)$, and differentiate with respect to σ. This procedure confirms that, given the assumptions we have already stated, $\frac{\partial W^*}{\partial \sigma} < 0$ anywhere above point B. (we provide an algebraic proof in the Appendix). In other words, shifting away from standard-only policy and toward a policy that includes some carbon pricing (while reducing the same amount of CO_2) improves overall welfare. Further deriving the second derivative confirms that $\frac{\partial^2 W^*}{\partial \sigma^2} < 0$. In other words, an incremental reduction in the standard improves welfare by a larger amount at first and less so as the policy mix shifts toward the optimal pricing-only policy. We illustrate this non-linearity in Figures 7 and 8 in the Appendix using a sample parameterization of our theoretical model. In the next section, we explore the same effect with previously published energy system models.

3 Experiments with energy system models

We model the cost-efficiency tradeoff between different climate policy portfolios in the US using two different techno-economic models. First, we employ EPPA (Ghandi and Paltsev (2020)), an economy-wide model, to model low-carbon standards in the electricity and transportation sectors in combination with an economy-wide carbon price. Second, we employ GenX (Jenkins and Sepulveda (2017)). GenX is a detailed power system planning model that models hourly electricity demand, supply, and system constraints. Therefore, it allows us to model policy tradeoffs within a more detailed representation of the electricity sector.

3.1 Experimental procedures

Our modeling experiment with each techno-economic model proceeds along the following steps. We select a given low-carbon standard policy (such as an RPS) of a given stringency and run the model to obtain an equilibrium solution. We then introduce a cap-and-trade policy that caps on CO_2 emissions at the level achieved by the standard. Next, we run the model iteratively for different levels of the standard (for the purposes of this description, we denote these scenarios using the index $i = \{1, ..., n\}$). The levels of the standard start from the initial stringency level and end with a level of zero, or until reductions in the standard cease to decrease overall policy cost. This procedure provides a set of scenarios representing different climate policy portfolios that reduce the same amount of CO_2. In total, we run five such scenarios, which we show in Table 1. A set of five scenarios is run for different types of standards to examine how results may change depending on whether, for example, the low-carbon standard is an RPS or a CES.

For each climate policy mix, we estimate the level of abatement caused by the carbon pricing policy. To do this, we run the model without a CO_2 cap for each level of the standard σ_i (resulting in the same number of alternative no-cap scenarios, which we denote using the index $j = \{1, ..., n\}$). The amount of abatement caused by cap-and-trade is quantified as: $A_i = E_j - E_i$, where E_j and E_i are the CO_2 emission levels without the cap and with the cap respectively. In other words, we define the abatement caused by cap-and-trade as the amount of emissions that would have occurred without the cap. We use this estimate as a measure of the extent to which a given policy mix relies on cap-and-trade as opposed to a standard.

The energy system models are used to quantify policy cost for the all policy portfolios. When modeling with GenX, policy cost represents the increase in electricity system cost in scenario i relative to electricity system cost under a baseline, no-policy scenario. When using EPPA, we estimate policy cost as the decrease in aggregate macroeconomic consumption, a common measure of policy welfare effect (Paltsev et al. (2005)), in scenario i relative to consumption under a reference, no-policy scenario.

The version of EPPA used here was described by Ghandi and Paltsev (2020). As a Reference scenario, we use the "Paris Forever" scenario, which assumes implementation of commitments under the Paris Agreement and no additional policy after 2030. We test the impacts of more stringent climate policies, which are meant to be illustrative of potential future policy. We implement low-carbon standards in the US for the year 2050, with a stringency that rises linearly from present-day values to their given value in 2050. The standard policies we model include: a 100% RPS, 100% CES, and 80% CAFE standard.[9] The first two policies apply to the electricity sector, while the CAFE standard applies to transportation. The RPS policy represents a mandate with tradable certificates that encourage greater use of renewables including wind, solar PV, hydropower, and biomass. The CES policy functions in the same way but includes nuclear and CCS technologies (which receive a full credit for each unit of production, thus assuming a 100% capture rate). The CAFE standard is a miles-per-gallon standard for all on-road fuel consumption that mandates a given percent improvement relative to the year 2005 (Karplus and Paltsev (2012)). In EPPA, this standard

[9] Our Reference scenario includes a CAFE standard, which mandates a 37% improvement in average fuel efficiency by 2040 relative to 2015 consistent with the Paris Forever scenario from Ghandi and Paltsev (2020).

Table 1: Policy scenarios

	EPPA scenarios			GenX scenarios	
Policy scenario	RPS-based policy	CES-based policy	CAFE-based policy	RPS-based policy	RPS-based policy
1	RPS 100%	CES 100%	CAFE 80%	RPS 100%	RPS 100%
2	RPS 90% + CAT*	CES 90% + CAT	CAFE 70% + CAT	RPS 95% + electricity CAT	RPS 95% + economy-wide CAT
3	RPS 80% + CAT	CES 80% + CAT	CAFE 60% + CAT	RPS 90% + electricity CAT	RPS 90% + economy-wide CAT
4	RPS 70% + CAT	CES 70% + CAT	CAFE 50% + CAT	RPS 80% + electricity CAT	RPS 80% + economy-wide CAT
5	CAT	CAT	CAT	Electricity CAT	Economy-wide CAT
Emission reductions for each mix 1-5	Equivalent to RPS 100%	Equivalent to CES 100%	Equivalent to CAFE 80%	Equivalent to RPS 100%	Equivalent to RPS 100%

*All CAT scenarios in EPPA are economy-wide

encourages improvement in fuel efficiency, reduction in gasoline-fueled miles traveled, or adoption of cleaner technologies such as hybrids or battery-electric vehicles. We combine each of these standards with an economy-wide cap-and-trade, which caps CO_2 emissions at the level achieved by each of the standards. Consistent with the experimental procedure described above, we model alternative policy portfolios that, for each type of standard, cap emissions at the same level but vary in the stringency of the standard. All policy scenarios are listed in Table 1.

The GenX model used in this paper is the version parameterized and configured by Dimanchev, Hodge, and Parsons (2020) based on data for the U.S. New England power system. The model optimizes capacity expansion and dispatch decisions to meet projected electricity demand for all 8760 hours in the year 2050. The model also accounts for unit commitment decisions and operational constraints on thermal plants, battery storage, and demand response, as well as hourly renewable availability. In this paper, we represent only New England and exclude connections to neighboring electricity markets. For a Reference scenario we model the system without any climate policy[10]. We then implement different policy portfolios containing an RPS and a cap-and-trade policy. See Table 1 for all alter-

[10] The no policy model solution for 2050 already captures a significant penetration of renewables, which may be considered consistent with the "Paris Forever" scenario we use in EPPA

native policy scenarios tested. Applying the experimental procedure described above, we model different combinations of an RPS and a carbon pricing that fully decarbonize the electricity sector (the equivalent of a 100% RPS). We choose to model somewhat different increments of RPS stringency in GenX compared to EPPA in order to more fully represent the spectrum of costs across different policy mixes. We also model an RPS combined with an economy-wide cap-and-trade policy.

Modeling an economy-wide carbon pricing policy in GenX is done in a reduced-form manner. We do this by making CO_2 reduction credits available to gas-fired power plants (the only emission source in our model) by increasing the cost of gas fuel. Gas plant owners are effectively able to purchase CO_2 allowances from other economic sectors where emission reductions may be cheaper. Our assumption for the price of CO_2 allowances is derived from modeling in EPPA. We use EPPA to model a cap-and-trade policy that achieves the same amount of emission reductions as a national 100% RPS. This results in a carbon price of $180/tCO2. This price represents the marginal cost of abatement in a cap-and-trade without the presence of an RPS. If an RPS is present, however, the additional abatement required from cap-and-trade sectors would be lower, thus lowering the economy-wide carbon price. To more accurately represent how much the economy-wide cap-and-trade allowances may cost with both policies in place, we calculate the corresponding average carbon price. Assuming a linear relationship between the carbon price and the level of abatement, the average carbon price would be half as high as the marginal price, or $90/tCO2. This is a conservative assumption as in most of our scenarios the cap-and-trade policy is responsible for less than half of all abatement. As we discuss below, our results are robust to different assumptions for the cost of carbon allowances.

3.2 Economy-wide climate policy: EPPA modeling

Figure 3 illustrates how the costs of a climate policy portfolio vary depending on its reliance on a standard or on carbon pricing. Each line shows results for a different kind of standard, which we combine with a cap-and-trade (CAT). The values on the far left represent a policy portfolio that relies purely on a low-carbon standard. The values to the right represent gradual reductions in the stringency of the standard and an associated increase in the extent to which the policy relies on the cap-and-trade policy to achieve the required amount of emission reductions.

The results are consistent with our theoretical analysis. A policy that combines carbon pricing and a standard cost less than a pure standard-based policy (our first proposition). In addition, this efficiency benefit of carbon pricing exhibits diminishing marginal returns (our second proposition and primary research question). Modest carbon pricing leads to disproportionately large cost savings. The figure represents the role of carbon pricing in the policy portfolio on the horizontal axes. In panel a., this is expressed as the inverse of the stringency of the standard (the lower the standard, the greater the role of carbon pricing). In panel b., the role of carbon pricing is expressed as the percentage of abatement caused by the cap-and-trade policy (panel b.). In both cases, the relationship between total policy costs (on the y-axis) and the extent of the role of carbon pricing in the policy portfolio is non-linear (specifically, convex).

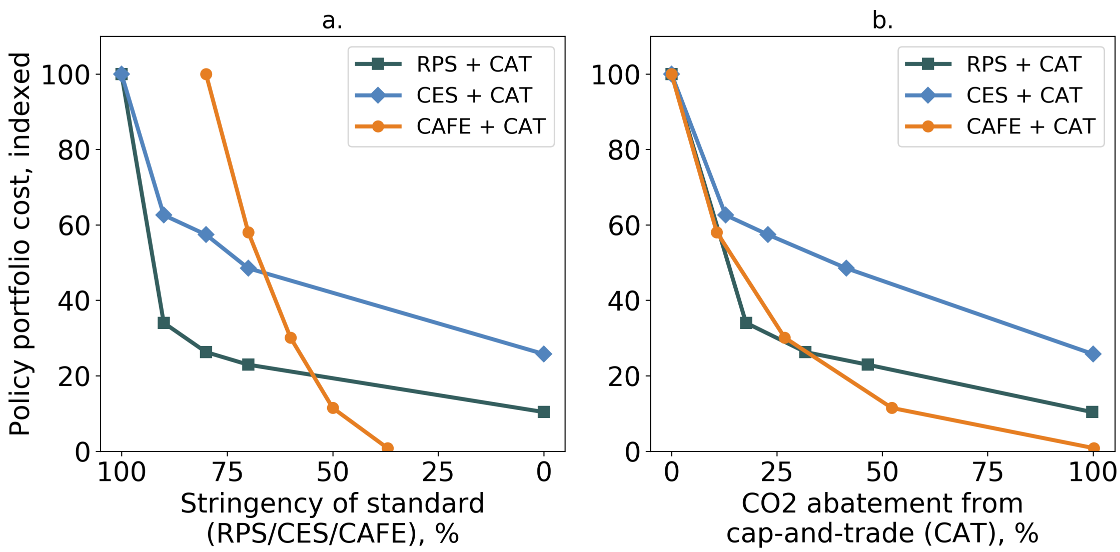

Figure 3: Cost of alternative climate policy portfolios modeled in EPPA
All policy portfolios on a given curve reduce the same amount of CO_2. "Policy cost" refers to the decrease in macroeconomic consumption relative to the Reference scenario. All policy costs have been indexed, whereby 100 represents the cost of the most expensive policy option: the scenario relying purely on a standard and not on carbon pricing (the left-most values in each panel).

Panel a. in Figure 3 illustrates how even small reductions in the standard, accompanied by a cap-and-trade or a carbon tax to keep CO_2 constant, lead to relatively large reductions in climate policy costs. We first describe the results with respect to an RPS, then move to a CES and CAFE standards. A policy portfolio including a 90% RPS and a cap-and-trade (second square from the left on the dark-blue line) reduces policy cost by 66% relative to a 100% RPS scenario that achieves the same emission reductions (first dot on the dark blue line). Panel b. in Figure 3 illustrates these results with respect to the amount of abatement caused by the cap-and-trade policy. In the 90% RPS plus carbon pricing scenario, only 18% of the emission reductions come from the cap-and-trade policy (second square from the left on the dark blue-line in panel b). As we move rightward, we see the results of Proposition 2 (we discuss exceptions further below). An 80% RPS plus carbon pricing leads to additional cost reductions, but not as severe as moving from a 100% RPS to a 90% RPS. In the 80% scenario, costs are 74% lower than relying completely on an RPS. Only 32% of the reductions are coming via carbon pricing. The slope of panel a. continues to flatten as we move rightward. In panel b. the slope is largely linear after the initial cost reduction. Comparing the leftmost and rightmost values shows our results replicate past work that suggests the costs of relying solely on an RPS are larger than the costs of relying only on carbon pricing (ten times larger according to our results here).

We find similar results with a CES although not as drastic. This can be explained by the higher cost-efficiency of the technology-neutral CES policy relative to the RPS. Moving from a 100% CES with no carbon pricing to a 90% CES with carbon pricing costs fall by nearly 40% (the first diamond of the light-blue line). In this scenario 13% of the carbon reductions result from adding the carbon price on top of the 90% CES. Costs continue to fall as we rely more and more on carbon pricing, but by a decreasing amount.

Our CAFE analysis begins with a standard equal to an 80% reduction in average national miles per gallon. We choose this level of stringency because the very rapid rise in estimated policy costs at higher levels of stringency make results more difficult to interpret. The results show that relying on a 70% reduction standard and a cap-and-trade reduces policy costs by over 40% relative to an 80% standard without cap-and-trade (second circle in panel a.). In the 70% scenario, only 11% of the carbon reductions come from carbon pricing as illustrated by the second circle of the orange line in panel b. Policy costs continue to fall rapidly although, consistent with Proposition 2, flatten somewhat. Costs decrease dramatically in the final scenario (featuring a 37% CAFE) to 1% of the costs of the 80% CAFE.

We note that Figure 3 does not always show continuous flattening relationships between policy cost and the role of carbon pricing. For example, the slope of the light blue line in panel a. steepens again between the third and fourth points, and so does the dark blue line between the fourth and fifth points in panel b. These observations suggest that the decreasing marginal benefit of carbon pricing (our Proposition 2) is not always monotonic for different increments of carbon pricing. In other words, these results show Proposition 2 does not hold for every incremental change in the role of carbon pricing in the policy mix, even though it holds more generally across larger increments. The presence of such exceptions can be attributed to non-monotonic (i.e. step-like) changes in a model's welfare or cost functions. Our theoretical model does not exhibit such results because it assumes the utility and product cost functions are monotonic (i.e. smooth), which produces monotonic indifference curves, the slope of which is a key part of our proof. On the other hand, EPPA exhibits non-monotonic changes. Specifically in the case of the CES scenarios, we observe changes in the marginal cost of the CES policy (i.e. the shadow value of the constraint) that correspond to the results in Figure 3, namely the slope steepening between the 80% and the 70% scenarios relative to the slope between the 90% and the 80% scenarios.

We also report carbon prices from the resulting policy portfolios in Figure 9 in Appendix section 5.2. The results show that the benefits of carbon pricing similarly diminish with the level of the price.

The cost reductions caused by incorporating carbon pricing in climate policy can be mainly explained by the availability of cheaper CO_2 abatement options outside of the scope of the standard. Figure 4 illustrates emission reductions by sector for each of the policy portfolios featuring an RPS. Under a 100% RPS, reductions occur primarily in the electricity sector (far left bars). In contrast, combinations of a less stringent RPS and a cap-and-trade result in emission reductions across sectors. This shows that carbon pricing lowers policy costs by incentivizing cheaper abatement options, which in the EPPA model occur in the industry, refining, and residential sectors. Another source of inefficiency for the RPS 100% policy is the offseting effect visible in Figure 4. As illustrated, the reductions in the electricity sector are partially offset by higher emissions in transportation and residential sectors. This is caused by higher electricity prices, which decrease the uptake of electric vehicles and increase use of fossil fuels for residential energy.

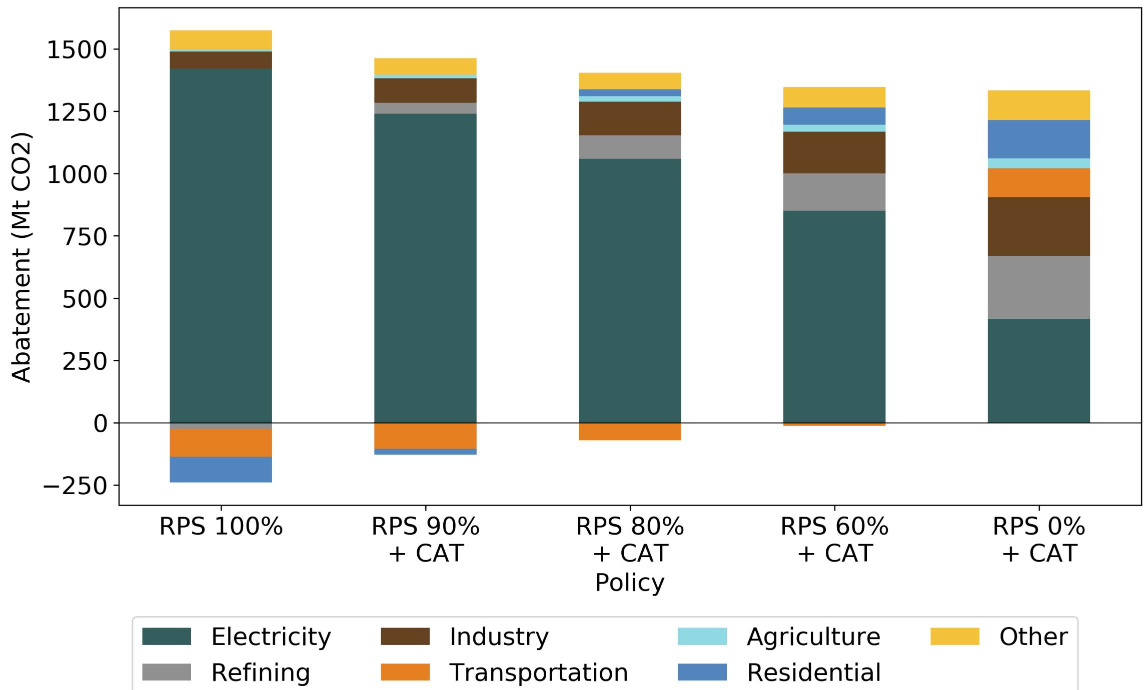

Figure 4: CO_2 abatement by sector for alternative climate policy portfolios
All policy portfolios reduce the same amount of total CO_2.

We also calculate the shadow value of the RPS and CES constraints, expressed in dollars per ton of abatement.[11] The shadow values reflect the *marginal* cost of carbon reductions under the two policies—the cost to society from the last ton of carbon abated. The left panel of Figure 5 plots these calculations. In the right panel, we report the carbon price generated by the cap-and-trade policy.

The figure implies that the marginal cost of both standards increases considerably after 80%. The shadow values of both a 70% or 80% RPS are roughly $150 per ton of CO_2. These imply that if the social cost of carbon is above $150, the final ton of abatement under the RPS improves social welfare. Similarly, the shadow values of both a 70% or 80% CES are also roughly $150 per ton of CO_2. Beyond an 80% standard, the marginal costs of an RPS increase considerably, while marginal costs of the CES increases considerably beyond 90%. The marginal cost of the RPS at 80% exceeds $2,200 per ton; it exceeds $2,600 per ton at 100%. The marginal cost of the CES is $276 at 90% and $1,686 at 100%. These calculations

[11] We calculate these implicit carbon prices by modeling RPS and CES standards with marginally relaxed (by 2%) stringencies compared to our original scenarios (e.g. modeling a 98% RPS to be compared to the 100% RPS). This is done in the absence of a CO_2 cap. We then calculate the change in social costs and emissions under the slightly relaxed standard. We are in the process of calculating similar shadow values for GenX.

underscore the important contribution of carbon pricing to keep down the cost of deep decarbonization goals. The marginal cost of relying almost exclusively on standards for deep decarbonization goals is relatively high. Carbon pricing can keep society from traveling up the steepest part of a RPS or CES's marginal cost curve, yielding huge efficiency gains.

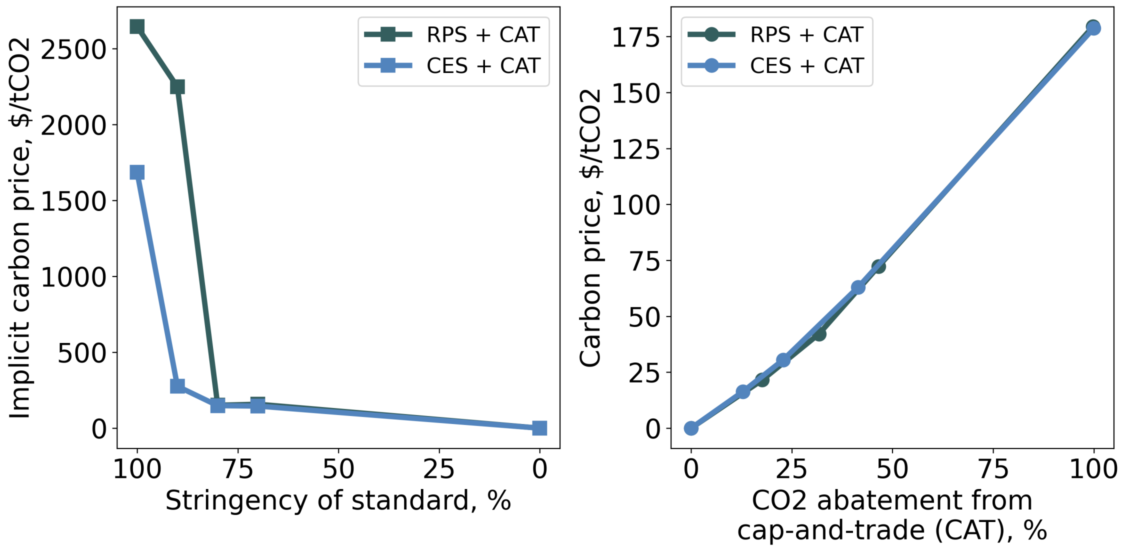

Figure 5: Shadow values of the standards constraint at different stringencies
All policy portfolios on a given curve reduce the same amount of CO_2. The implicit carbon price is the marginal cost of the standard constraint calculated by relaxing the constraint by 2% and calculating the ratio of the reduction in social costs to the increase in emissions.

3.3 Electricity sector climate policy: GenX modeling

Figure 6 displays how policy costs vary across different combinations of RPS and carbon pricing modeled using GenX. Consistent with our previous results, we find that the efficiency benefit of carbon pricing exhibits diminishing marginal returns. The figure represents the role of carbon pricing in the policy portfolio on the horizontal axes as either the inverse of the RPS stringency (panel a.) or the percentage of abatement caused by the cap-and-trade policy (panel b.).

The dark blue line in Figure 6 illustrates different combinations of RPS and an electricity sector cap-and-trade. We observe similar cost reductions as those derived from EPPA. For example, a policy portfolio that includes a 95% RPS and a cap-and-trade reduces costs by 51% relative to the 100% RPS (shown by the third square from the left). As illustrated in panel b., these cost reductions occur with the cap-and-trade providing only 23% of total

CO_2 abatement. Increasing further the reliance on carbon pricing, the RPS 90% scenario reduces costs by 59% relative to the 100% RPS (fourth dark blue square in panel a.), as cap-and-trade delivers 42% of total abatement (fourth dark blue square in panel b.). This again demonstrates Proposition 2.

Cost reductions are driven by the use of cheaper zero-carbon technologies that are otherwise assumed ineligible for the RPS. In particular, relaxing the RPS leads to to the use of gas with CCS (we assume a 100% CO_2 capture rate, representing, for example, an Allam cycle plant). This allows the system to reduce the oversizing of variable renewables, which is the primary driver behind the non-linear increase in policy costs associated with high renewable penetration (Sepulveda et al. (2018)).

We find similar results under our economy-wide cap-and-trade scenario (light blue line in Figure 6). In this scenario, reducing the stringency of the RPS leads to increasing usage of combined-cycle gas turbine plants (without CCS). As described in section 3.1, these gas plants pay a flat \$90/tCO_2 carbon price for every ton of CO_2 emitted, which is assumed to effectively offset their emissions. The results show that a policy portfolio that includes a 95% RPS and an economy-wide cap-and-trade reduces costs by 65% relative to the 100% RPS (shown by the third square from the left in panel a.). In this scenario, only 23% of the emission reductions are driven by the cap-and-trade policy (panel b.). The reductions in costs flatten as the stringency of the standard is reduced and the policy mix increases reliance on cap-and-trade. For example, in the 90% RPS scenario, costs are 75% lower than in the 100% RPS scenario (panel a.) with cap-and-trade accounting for 42% of emission reductions.

The economy-wide cap-and-trade scenario demonstrates how incentivizing CO_2 abatement options from other economic sectors drastically reduces the costs of stringent RPS policies. Policy makers can thus lower the cost of climate policy by implementing carbon pricing that covers additional sectors and incentivizes a broader swath of producers to undertake least cost abatement options. These results are robust to different carbon price assumptions as the assumed cost incurred by gas plants for carbon allowances are relatively small. For example, in a 90% RPS scenario, the total cost of the \$90/tCO_2 carbon allowances is only 4% of the total electricity system cost.

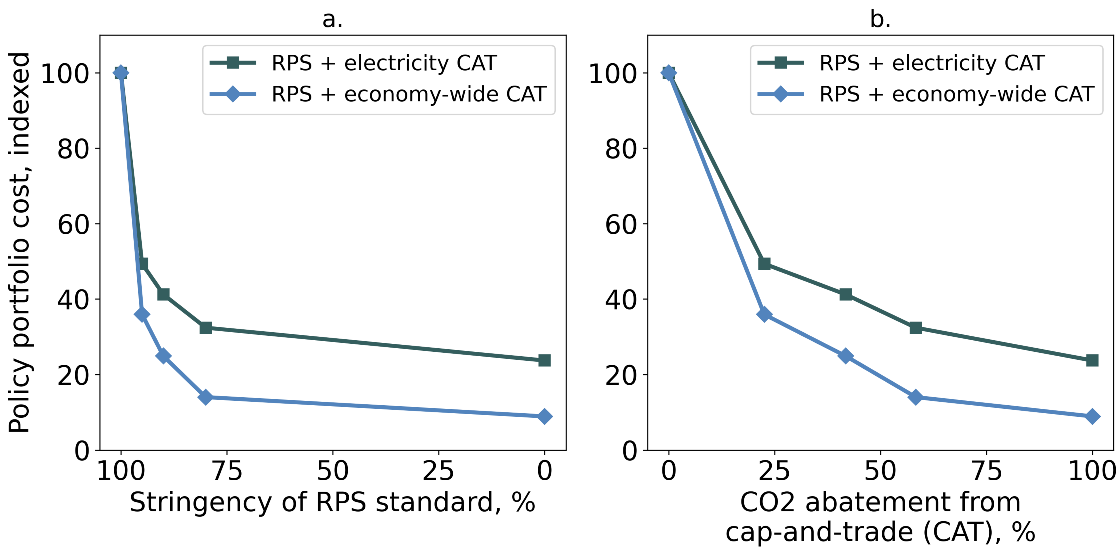

Figure 6: Cost of alternative climate policy portfolios modeled in GenX
All policy portfolios on a given curve reduce the same amount of CO_2. "Policy cost" refers to the increase in total electricity system costs from a no-policy scenario. System costs include cost of: investment, generation, demand shifting, storage, demand curtailment and starting of thermal plants).

4 Discussion and conclusions

Through both theory and modeling we demonstrate two propositions. First, a combination of carbon pricing and a standard costs less than a standard-only policy that reduces the same amount of CO_2. The cost is lowest when relying fully on carbon pricing. This result reflects the cost-saving (i.e. efficiency) benefit of incorporating carbon pricing into climate policy. Second, the cost-saving benefit of incorporating carbon pricing is large at first and diminishes the more a policy relies on carbon pricing as opposed to a standard. This result reflects what we call the diminishing marginal benefit of carbon pricing. It underscores that even a modest carbon price can have large efficiency benefits.

Our results show that these propositions hold in a variety of cases. Our theoretical model suggests that when a low-carbon standard and carbon pricing are applied to the same set of products, the latter provides a cost-saving benefit by incentivizing a more efficient combination of products. Next, our modeling in EPPA illustrates the tradeoff between a low-carbon standard in one sector (electricity) and an economy-wide carbon pricing. The results show that carbon pricing provides cost-saving benefits by incentivizing CO_2 reductions in other economic sectors. Finally, our modeling in GenX shows that an electricity-sector carbon price provides cost-saving benefits relative to an electricity-sector standard by incentivizing cheaper technological options outside of the scope of the standard. The results from both EPPA and GenX support our theoretical finding that the cost-saving benefit of carbon pricing is large at first and diminishes with the extent of the role[12] played by carbon pricing in the policy mix.

These results have several policy implications. Lawmakers can drastically reduce policy costs if they combine low-carbon standards with modest carbon pricing, relative to the cost of relying on standards alone. By implementing modest carbon pricing, policy makers would accomplish a disproportionately large share of the cost savings of economically optimal carbon pricing. These findings are particularly relevant for the design of standard-based climate policy packages, exemplified by recent national proposals (House Committee on Energy and Commerce (2020); House Select Committee on the Climate Crisis (2020)).

A general finding of this paper is that, in the presence of higher political costs associated with carbon pricing, there are advantages in combining alternative policy tools, such as standards and carbon pricing, into a hybrid policy portfolio. Policy debates have been previously framed as a choice between such options. However, the multitude of criteria against which policies will be evaluated suggest there is no "silver bullet" approach to climate policy. Combining standards with carbon pricing could balance the distinct advantages of each approach with respect to different policy making criteria. This paper focuses on two criteria: the amount of CO_2 reduction and the economic cost of future policy. These criteria are collectively captured by a policy's cost-efficiency, expressed as the cost of a given amount of CO_2 abatement. When it comes to cost-efficiency, we argue that finding the right combination between a standard and a carbon price depends on the marginal cost-efficiency benefit of carbon pricing. Our finding that modest carbon pricing has a relatively large marginal benefit may justify including modest carbon prices in climate policy packages. Future research could further examine how different policy mixes differ with respect to societal criteria other than cost-efficiency. Envisioning alternative policy tools in concert as we do in this paper may provide opportunity for consensus between advocates of either approach.

[12] Defined, for example, as the share of total emission reductions attributed to the carbon pricing policy.

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5 Appendix

5.1 Proofs

As discussed in section 2, the first proposition we set out to prove is that welfare is improved by shifting away from a pure standard-based climate policy toward a policy that includes carbon pricing. Expressed algebraically in our theoretical framework, the proposition states that $\frac{\partial W^*}{\partial \sigma} < 0$.

5.1.1 Proof for proposition 1.

At the optimal welfare point, the two policy constraints bind such that:

$$\frac{q_L}{(q_H + q_L)} = \sigma$$

$$q_H \beta_H + q_L \beta_L = c$$

From this system of equations we can solve for the quantities of both products, which we express as functions of σ:

$$q_H = F(\sigma) = \frac{c(1-\sigma)}{\beta_H(1-\sigma) + \sigma\beta_L}$$

$$q_L = G(\sigma) = \frac{c\sigma}{\beta_H(1-\sigma) + \sigma\beta_L}$$

The optimal welfare W^* can therefore be expressed as:

$$W(\sigma) = U(F(\sigma), G(\sigma)) - C_H(F(\sigma)) - C_L(G(\sigma))$$

Before differentiating W, we differentiate F and G with respect to σ:

$$\frac{dF}{d\sigma} = -\frac{c\beta_L}{(\beta_L - \beta_H)\sigma + \beta_H)^2} < 0$$

$$\frac{d^2F}{d\sigma^2} = \frac{2\beta_L(\beta_L - \beta_H)c}{((\beta_L - \beta_H)\sigma + \beta_H)^3} < 0$$

$$\frac{dG}{d\sigma} = \frac{c\beta_H}{((\beta_L - \beta_H)\sigma + \beta_H)^2} > 0$$

$$\frac{d^2G}{d\sigma^2} = \frac{-2\beta_H(\beta_L - \beta_H)c}{((\beta_L - \beta_H)\sigma + \beta_H)^3} > 0$$

While the signs of the first derivatives of F and G are clear, we also note that the signs of the second derivatives can be verified for all $\beta_L < \beta_H$. The signs of the first derivatives have the intuitive meaning that as σ increases, the optimal amount of q_L increases and of q_H decreases. The signs of the second derivatives mean that the marginal increase and decrease in the optimal amounts of q_L and q_H respectively both increase as σ increases.

Next, we explore how W^* varies with σ

$$\frac{\partial W^*}{\partial \sigma} = \frac{\partial U}{\partial F}\frac{dF}{d\sigma} + \frac{\partial U}{\partial G}\frac{dG}{d\sigma} - \frac{\partial C_H}{\partial F}\frac{dF}{d\sigma} - \frac{\partial C_L}{\partial G}\frac{dG}{d\sigma}$$

$$= \frac{dF}{d\sigma}(\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}) + \frac{dG}{d\sigma}(\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G})$$

This implies that $\frac{\partial W^*}{\partial \sigma} < 0$ when:

$$\frac{\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}}{\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}} < -\frac{\frac{dG}{d\sigma}}{\frac{dF}{d\sigma}}$$

Using the expressions for the derivatives of F and G, this can be re-written as:

$$-\frac{\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}}{\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}} > -\frac{\beta_H}{\beta_L}$$

Note that $-\frac{\beta_H}{\beta_L}$ is the slope of the cap-and-trade constraint (the dashed line in Figure 2). The expression on the left contains the ratio of the marginal utilities (net of cost) of each product, which is also their marginal rate of substitution. The negative signs makes the marginal rate of substitution equal to the slope of the welfare function (e.g. the indifference circle in Figure 2). Therefore, this inequality is true for all points where the slope of the welfare function is larger than the slope of the cap-and-trade constraint. This will be true for all points where the standard is binding. To illustrate, at point B in Figure 2, the slope of the welfare circle is equal to the slope the cap-and-trade constraint (dashed line). This is consistent with intuition that at this point welfare cannot be further improved by reducing the standard constraint, or, in other words, that $\frac{\partial W^*}{\partial \sigma} = 0$. At all points above B, the slope of the indifference circle increases beyond $-\frac{\beta_H}{\beta_L}$, resulting in: $\frac{\partial W^*}{\partial \sigma} < 0$.

5.1.2 Proof for proposition 2.

The second proposition is that efficiency benefits from shifting the policy mix from a standard toward carbon pricing exhibit diminishing marginal returns, or that $\frac{\partial^2 W^*}{\partial \sigma^2} < 0$. Differentiating, we find:

$$\frac{\partial^2 W^*}{\partial \sigma^2} = \frac{\partial^2 U}{\partial F^2}\frac{dF}{d\sigma}^2 + \frac{\partial U}{\partial F}\frac{d^2 F}{d\sigma^2} + \frac{\partial^2 U}{\partial G^2}\frac{dG}{d\sigma}^2 + \frac{\partial U}{\partial G}\frac{d^2 G}{d\sigma^2} -$$
$$- \frac{\partial^2 C_H}{\partial F^2}\frac{dF}{d\sigma}^2 - \frac{\partial C_H}{\partial F}\frac{d^2 F}{d\sigma^2} - \frac{\partial^2 C_L}{\partial G^2}\frac{dG}{d\sigma}^2 - \frac{\partial C_L}{\partial G}\frac{d^2 G}{d\sigma^2} =$$

$$= \frac{dF}{d\sigma}^2 \left(\frac{\partial^2 U}{\partial F^2} - \frac{\partial^2 C_H}{\partial F^2}\right) + \frac{d^2 F}{d\sigma^2}\left(\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}\right) +$$
$$+ \frac{dG}{d\sigma}^2 \left(\frac{\partial^2 U}{\partial G^2} - \frac{\partial^2 C_L}{\partial G^2}\right) + \frac{d^2 G}{d\sigma^2}\left(\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}\right)$$

For the two parenthetical statements on the left, we observe that their signs are negative as long as both of these second utility derivatives are non-positive, or $\frac{\partial^2 U}{\partial q_i^2} \leq 0$. This means that utility exhibits non-increasing returns to scale (which we assumed in the beginning). Given the square coefficient terms on the left, both left expressions have negative signs. Therefore, the whole expression will be negative if the two expressions on the right are together negative, i.e. if the following inequality holds:

$$\frac{d^2 F}{d\sigma^2}\left(\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}\right) + \frac{d^2 G}{d\sigma^2}\left(\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}\right) < 0$$

As before, we can rewrite this as:

$$\frac{\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}}{\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}} < -\frac{\frac{d^2 G}{d\sigma^2}}{\frac{d^2 F}{d\sigma^2}}$$

Using the expressions for $\frac{d^2 F}{d\sigma^2}$ and $\frac{d^2 G}{d\sigma^2}$ derived before, we find that this expression is equivalent to the statement which we proved above:

$$-\frac{\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}}{\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}} > -\frac{\beta_H}{\beta_L}$$

Therefore, $\frac{\partial^2 W^*}{\partial \sigma^2} < 0$. We have shown this is the case at least for all points where the slope of the welfare function exceeds the slope of the cap-and-trade constraint.[13]

5.1.3 Illustrative theoretical results

To demonstrate the propositions, we parameterize our theoretical model and illustrate how welfare varies across different policy mixes. We use a simple quadratic cost function for q_H, reflecting rising marginal costs: $C_H(q_H) = q_H^2$ and a similar higher-cost function for the low-carbon product: $C_L(q_L) = 10q_L + q_L^2$. We use a simple Constant Elasticity of Substitution utility function assuming perfect substitutability and decreasing returns to scale (reflecting diminishing marginal utility): $U(q_H, q_L) = 100(q_H + q_L)^{1/2}$. The solution to the unconstrained welfare optimization problem is $q_H = 7.7$ and $q_L = 2.7$, with corresponding welfare and emissions of 228.9 and 8.0, respectively. The share of the low-carbon product is 26%. Assuming $\beta_H = 0.9$ and $\beta_L = 0.4$, total CO_2 emissions are equal to 8.

We introduce an initial low-carbon standard: $\sigma_{initial} = 0.6$. The new optimal solution is now $q_H = 3.9$ and $q_L = 5.8$. This policy reduces emissions to 5.8, and reduces welfare to 204.3.

Next, we explore how this policy can be improved with carbon pricing (a cap-and-trade policy). We set a CO_2 cap constraint to reduce emissions by the same amount, down to 5.8. If we remove the standard constraint, we achieve the optimal climate policy solution. At this point the share of the low-carbon product is 31%, with corresponding welfare of 220.2.

We explore the space between standard-only and pricing-only policies by varying σ between the initial value, $\sigma_{initial} = 0.6$, and the optimal share, 0.31. We record the resulting welfare at each level of σ. For illustrative purposes, we convert welfare into policy cost. The cost of a certain policy scenario is defined as the loss in welfare relative to the unconstrained optimal welfare. $C_i = W^*_{opt} - W^*_i$, where W^*_{opt} is the unconstrained optimal welfare.

Figure 7.a shows resulting policy costs against the standard constraint. Consistent with our analysis above, reducing the standard improves welfare. This improvement exhibits diminishing marginal returns and tends toward zero as the σ approaches the optimal low-carbon share of 31%.

Changes to the main parameters of our model do not alter the non-linearity of the policy cost curve. However, they change the range of the low-carbon standards over which we

[13] The additional negative terms of the $\frac{\partial^2 W^*}{\partial \sigma^2}$ suggest that this is true in some additional cases but we do not explore these for the purposes of our research question.

observe changes in policy costs. Panel b. in Figure 7 shows the results after setting $\beta_L = 0$ (representing a zero-emission product). In this case the optimal low-carbon share is higher (at 51%), and as a result, policy cost reductions converge to zero at this point. Panel c. shows the results for a more stringent standard policy, where $\sigma_{initial} = 0.9$. The optimal low-carbon share under an equivalent cap-and-trade policy (one which reduces the same amount of emissions) is now 53%, higher than in panel a. We see the most extreme change in panel d., which represents a stringent standard, with $\sigma_{initial} = 0.9$, for a zero-emission product, with $\beta_L = 0$. In this case, the optimal low-carbon share under a cap-and-trade that achieves the same level of CO_2 abatement as the standard, is already 87%. In this case, the resulting welfare from a low-carbon standard is close to the optimal welfare under an optimal cap-and-trade policy (as seen from the range of the y-axis in panel d.). In other words, a cap-and-trade cannot improve much on the standard. The difference between the standard and cap-and-trade in this case tends toward zero as we consider a stricter standard. If we consider a 100% low-carbon standard for a zero-emission product, then the cap-and-trade and the standard-based solutions will be the same in our theoretical model[14].

[14] While this may seem to suggest that a cap-and-trade is equivalent to a 100% zero-emission standard, this result stems from the fact that our framework is only modeling a two-product economy. This would change if additional low-carbon products existed, or if the purchase of emission reduction credits from other economic sectors was possible. If such alternative abatement options existed, a cap-and-trade would incentivize the lowest cost set of such options and deliver additional welfare improvements to the standard. This is shown in our energy system modeling results in section 3

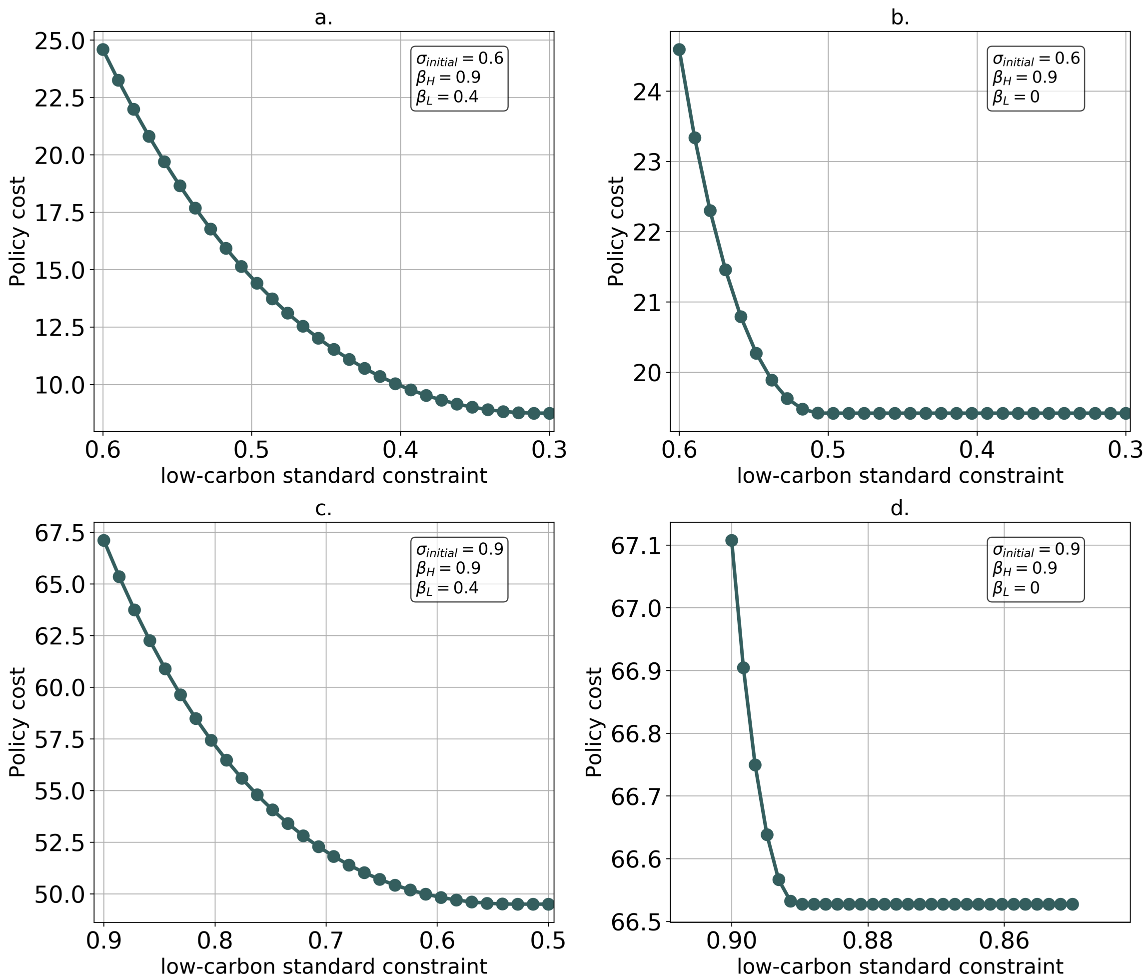

Figure 7: Indicative theoretical model results for the diminishing returns from carbon pricing
All points represent a policy mix comprising a standard and a cap-and-trade and achieving the same level of CO_2 abatement. As the standard is relaxed from left to right, the cap-and-trade plays a greater emission reduction role in the policy mix

The parameterized model allows us to explore how policy cost varies with the amount of abatement caused by cap-and-trade as opposed to abatement caused by the standard. We define the abatement from cap-and-trade A_i as the additional emissions that would have happened if the cap was not in place (for any level of the standard, indexed as σ_i), such that: $A_i = c - (q_{Hi}\beta_H + q_{Li}\beta_L)$, where c is the CO_2 cap and q_{Hi} and q_{Li} are the optimal quantities produced at different levels of the standard σ_i in the absence of the cap constraint.

Figure 8 illustrates how policy cost varies with the amount of abatement from cap-and-trade. The figure's horizontal axis expresses the abatement from cap-and-trade as a percent of total abatement (total abatement equals the cap relative to emissions in the unconstrained solution). We find a non-linear (convex) relationship between policy cost and the share of CO_2 abatement caused by the cap-and-trade policy. This is consistent with our previous demonstration of the convex relationship between costs and the level of the standard. The range of policy costs once again varies depending on the chosen model parameters.

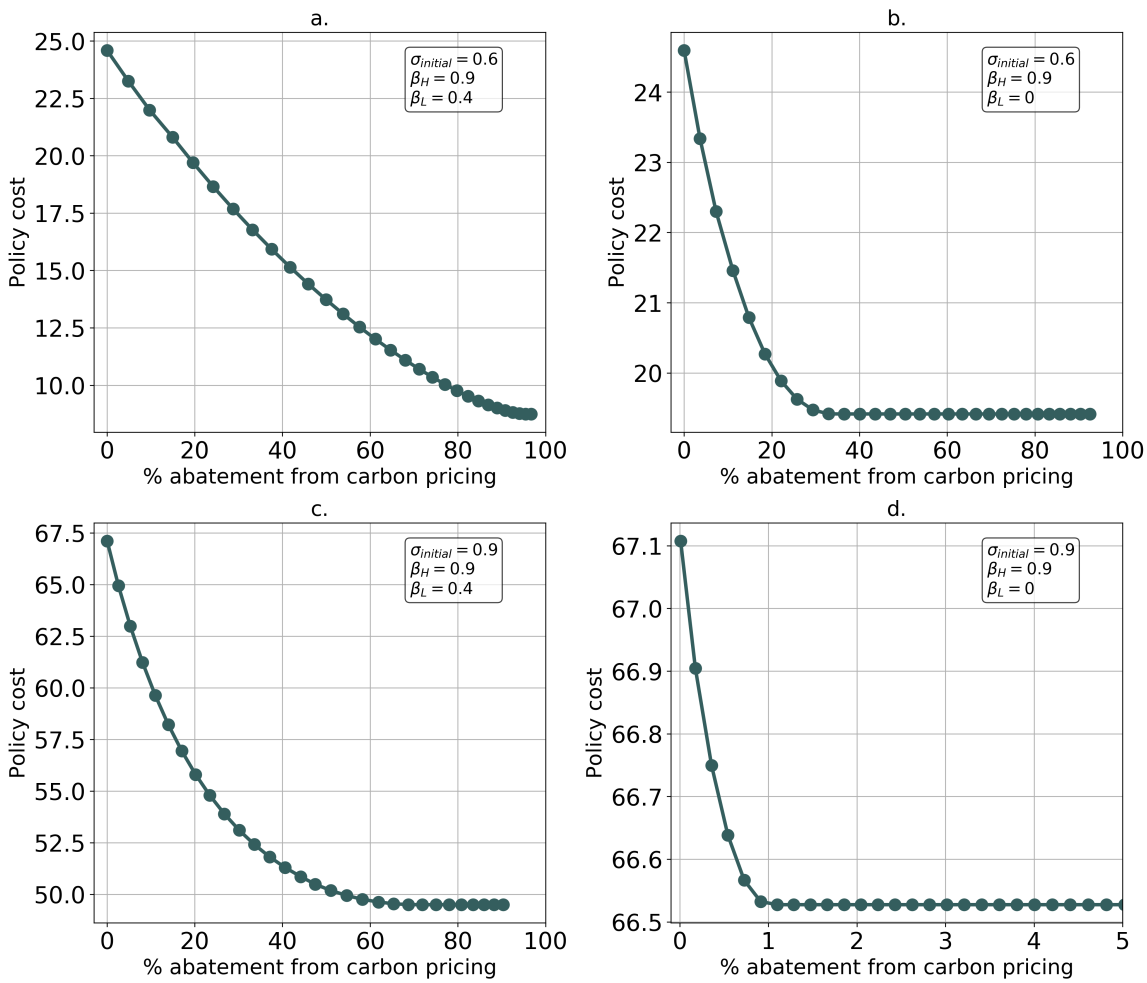

Figure 8: Indicative theoretical model results for the diminishing returns from carbon pricing-driven abatement
All points represent a policy mix comprising a standard and a cap-and-trade and achieving the same level of CO_2 abatement.

5.2 Additional figures

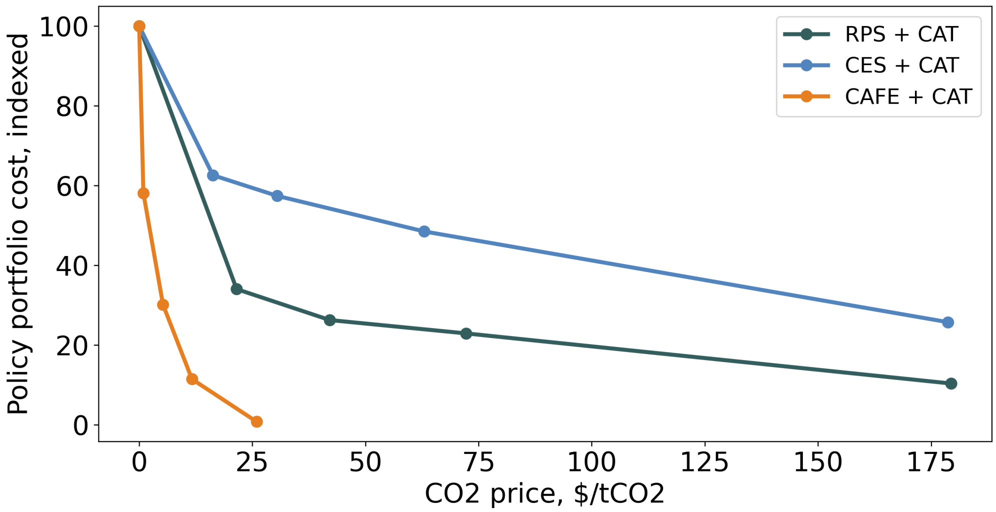

Figure 9: Cost of alternative climate policy portfolios relative to carbon prices
All policy portfolios on a given curve reduce the same amount of CO_2. "Policy cost" refers to the decrease in macroeconomic consumption relative to the Reference scenario. All policy costs have been indexed, whereby 100 represents the cost of the most expensive policy option: the scenario relying purely on a standard and not on carbon pricing (the left-most values in each panel).

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