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Designing climate policy mixes: Analytical and energy system modeling approaches

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ABSTRACT

A matter of debate in climate policy is whether lawmakers should rely on carbon pricing or regulations, such as low-carbon standards, to reach emission reduction goals. Past research showed that pricing is more cost-effective. However, previous work studied the two policies when implemented separately, in effect comparing two policy extremes. In contrast, we explore the full spectrum of climate policy mixes that include both types of policies but vary in how much they rely on each. We do this both analytically by extending previous theory and numerically with two energy system models. In line with past work, increasing reliance on pricing increases the cost-effectiveness of the policy mix. However, we show that this benefit exhibits diminishing marginal returns. Thus the gain in cost-effectiveness from complementing stringent standards with modest pricing is relatively large. Our results show that relying on pricing for 20% of emission reductions (and on a standard for 80%) reduces costs by 32%–57% compared to a standard-only approach. Importantly, trading off more of the standard for pricing delivers smaller and smaller gains in cost-effectiveness. For example, a policy mix that relies on each policy for 50% of emission reductions decreases costs by 60%–81%, which is already 71%–88% as cost-effective as the theoretically most cost-effective pricing-only policy.

1. Introduction

Economic research has traditionally recommended carbon pricing as the most efficient climate policy (Pigou, 1920; Stern, 2006; Tol, 2017). In practice however, policy makers have addressed climate change with mixes of different policies, only some of which have featured carbon pricing (European Council, 2021; California Air Resource Board, 2018). Climate policies other than carbon pricing have been justified by political constraints that limit the implementation of optimal carbon pricing (Lipsey and Lancaster, 1956; Jenkins, 2014; Wagner et al., 2015; Meckling and Kelsey, 2015; Tvinnereim and Mehling, 2018; Goulder, 2020), or by the need to correct multiple market failures that contribute to climate change (Stern, 2006; Jaffe et al., 2005; Borenstein, 2012; Lehmann and Gawel, 2013; Bhardwaj et al., 2020), which can be interpreted as constituting multiple policy targets (Tinbergen, 1952). This suggests that climate policy design involves choosing how to combine alternative policies into a climate policy mix (Stiglitz et al., 2017; Kern et al., 2019).

We frame climate policy mix design as a choice between different policy mixes that reduce the same amount of CO_2 but vary on a spectrum depending on how much they rely on each individual policy to reduce emissions. Past research extensively compared the extreme end-points of this spectrum, studying how individual policies compare when implemented separately (e.g. Goulder and Parry, 2008; Holland et al., 2009). Some studies have evaluated limited sets of policy combinations (Böhringer et al., 2009; Bertram et al., 2015; Rausch and Mowers, 2014; Kalkuhl et al., 2013; Millinger et al., 2022). However, it remains unclear how policy makers should choose between different combinations, or policy mixes.

To inform policy mix design, we draw on the well-known principle of marginalism (Marshall, 1890) to posit that the optimal combination of policies will depend on the marginal impact of trading off reliance on one policy for reliance on another policy (while keeping overall emissions the same). To illustrate the concept and facilitate clarity, this paper focuses on a two-policy example, though in practice government policy often combines more instruments (which is a multidimensional version of the problem we are considering here). In particular, we investigate policy mixes that combine carbon pricing and low-carbon standards, two popular policy types which are frequently compared in

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climate policy discussions (Rhodes and Jaccard, 2013; Siddiqui et al., 2016; Bergquist et al., 2020; Yeh et al., 2021; Bhardwaj et al., 2022, e.g.). To choose a policy mix in this case, a policy maker would have to know the marginal impacts of trading off reliance on a standard with reliance on pricing. Specifically, we define the marginal impact of increasing reliance on carbon pricing as the impact of reducing one more ton of emissions with carbon pricing and reducing one less ton with standards. The optimal mix is the one where the marginal benefit of trading off reliance equals the marginal cost. The marginal benefit of carbon pricing can be said to be its efficiency (i.e. cost-effectiveness); and its marginal cost can be said to be the forfeiting of the distinct benefits of standards, which may include knowledge spillovers and energy security (Borenstein, 2012; Lehmann and Gawel, 2013). For tractability, we focus on one side of this comparison and explore the marginal efficiency benefit of trading off standards for carbon pricing. Past research has not investigated such marginal effects to our knowledge. While there is extensive literature on the marginal impacts of specific policies (Böhringer et al., 2009; Kalkuhl et al., 2013; Bistline et al., 2019), we measure a marginal effect of trading off one policy for another. This analytical framework is this paper's first contribution to the literature.

The question we address is how the cost of a climate policy mix changes as the policy mix relies marginally more (or less) on carbon pricing (or standards). We first approach this question analytically, by extending a previously published theoretical model (Holland et al., 2009). This is another contribution of our paper. Next, we introduce a novel experimental procedure and apply it with two energy system models, which is the paper's third contribution. The procedure has three key features: it models two policies at once, generates alternative combinations (policy mixes) by trading off emission reductions by one policy for emission reductions by the other, and enforces an apples-to-apples consistency between all possible combinations by maintaining a constant amount of emission reductions. We are not aware of previous modeling that does all three.

This paper first shows that increasing the extent to which a policy mix relies on carbon pricing increases its cost-effectiveness, which is in line with past work. Specifically, our numerical results across both energy system models show that a policy mix that achieves 20% of its emission reductions via carbon pricing (and 80% via a standard) is 32%–57% less costly than a standard-only approach that achieves the same total emission reduction (these savings are equivalent to 37%–62% of the total savings delivered by the theoretically most cost-effective pricing-only policy). The main finding of this paper is that the cost-effectiveness gained from increasing reliance on carbon pricing exhibits diminishing marginal returns. A policy mix that relies on each policy for 50% of total abatement decreases costs by 60%–81% relative to a standard-only policy. These savings are also equivalent to 71%–88% of the total cost savings that can be achieved by a pricing-only policy relative to a standard-only one. This shows that a limited reliance on carbon pricing provides a disproportionately large share of the benefits offered by theoretically optimal carbon pricing. Equivalently, partial standards add relatively modest costs, which may be justified by their distinct benefits (which we leave for future work). Overall, these results lend support to combining both standards and pricing into policy mixes.

2. Methods

2.1. Analytical model

To represent the choice between different policy combinations of standards and carbon pricing, we extend the model by Holland et al. (2009). We first describe the model as developed by the authors and then discuss our extension. The model considers an economy with two products (assumed to be perfect substitutes): a high-carbon product with quantity of production denoted as q_H, and a low-carbon product: q_L. The two products have emission intensities β_H and β_L such that $\beta_H > \beta_L$ (our findings also 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: $C_L(q) > C_H(q)$. Society receives aggregate utility from consuming the two products expressed as a function $U(q_H, q_L) = U(q_H + q_L)$, with non-increasing returns to scale. The state of the economy is represented by the solution of the welfare maximization problem with welfare expressed as: $W = U(q_H, q_L) - C_H(q_H) - C_L(q_L)$. Climate policies are represented by two constraints. A standard policy mandates a share σ of the low-carbon product, expressed as the constraint: $\frac{q_L}{(q_H+q_L)} \geq \sigma$. Carbon pricing is represented by a constraint on CO_2 (reflecting a cap-and-trade policy): $q_H\beta_H + q_L\beta_L \leq c$.

Fig. 1.a represents this optimization problem graphically. Welfare is represented by indifference circles, with each circle representing a different level of welfare. Optimal welfare without climate policy, and ignoring the externality, is found at point X. The equilibrium solution after the implementation of the standard is point A, and a pricing-only policy (that reduces the same amount of emissions) would result in point B (Holland et al., 2009). 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. Carbon pricing is more efficient because it results in optimal consumption of both products.

We extend this model by including both the standard and carbon pricing constraints simultaneously, as a policy mix. Our focus is on the spectrum of policy mix choices, and this is found on the segment between points A and B (Fig. 1.b). The feasibility region is represented by the shaded areas in Fig. 1. The optimal solution of our model is found at the intersection of the two constraints. Point C in panel b illustrates one possible policy mix and its associated optimal solution. The figure shows that a mix of the two policies results in a more efficient outcome (higher welfare or, in other words, lower policy costs) than a pure standard-based policy. This reflects the efficiency advantage of carbon pricing. More importantly, the figure suggests that this efficiency advantage diminishes as point B is approached. Point C is the half-way reduction in the standard toward point B; specifically, point C was chosen as $\sigma_2 = \sigma_1 - \frac{1}{2}(\sigma_1 - \sigma_{opt})$. 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 from the figure that this non-linearity in the welfare improvement is caused by the curvature of the welfare circle. The following proposition formalizes this observation. The results section introduces an analytical proof of this proposition.

Proposition 1. $\frac{\partial^2 W^*}{\partial \sigma^2} \leq 0$. *That is, the welfare improvement from reducing the role of a standard (and increasing the role of pricing) in a policy mix exhibits diminishing marginal returns. The inequality is strict when the standard constraint binds.*

2.2. Energy system modeling

We perform numerical tests with two different energy system models: EPPA an economy-wide model (Ghandi and Paltsev, 2020), and GenX, a detailed electricity system model (Jenkins and Sepulveda, 2017) (described in Section 2.2.2). For this purpose, we implement a novel experimental procedure, which explores the spectrum of possible policy mixes while maintaining an apples-to-apples consistency between them by maintaining a constant amount of emission reductions (described in detail in the following section). In relation to the analytical model above, the energy system model experiments are analogous to exploring the spectrum between points A and B in Fig. 1. Aside from this similarity, we note that the analytical and energy system models

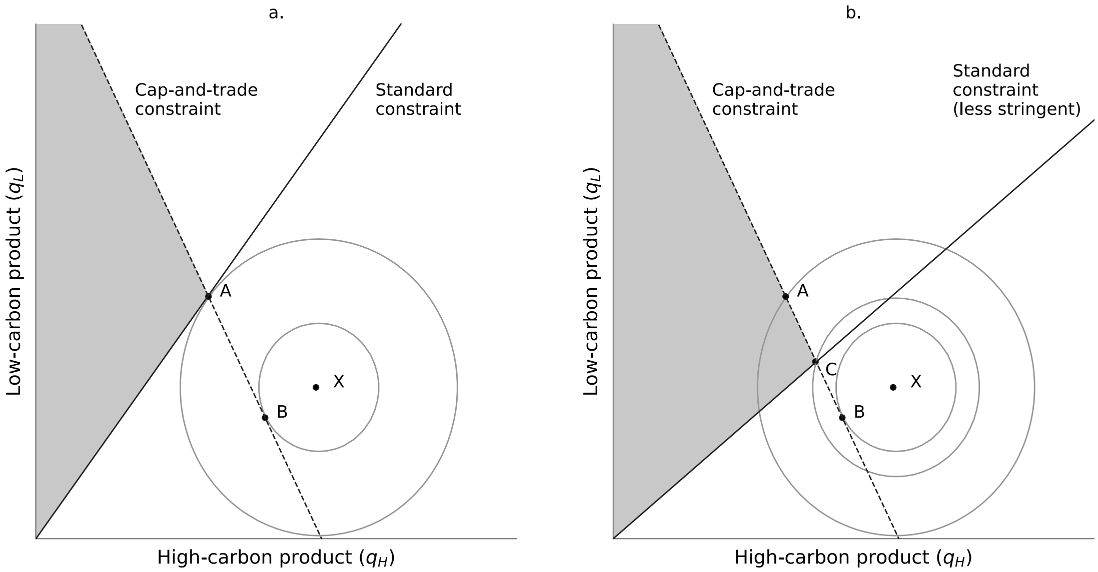

Fig. 1. Welfare maximization with policy constraints for a low-carbon standard and a cap-and-trade. The gray shaded area represents the feasibility region of possible combinations of q_H and q_L.

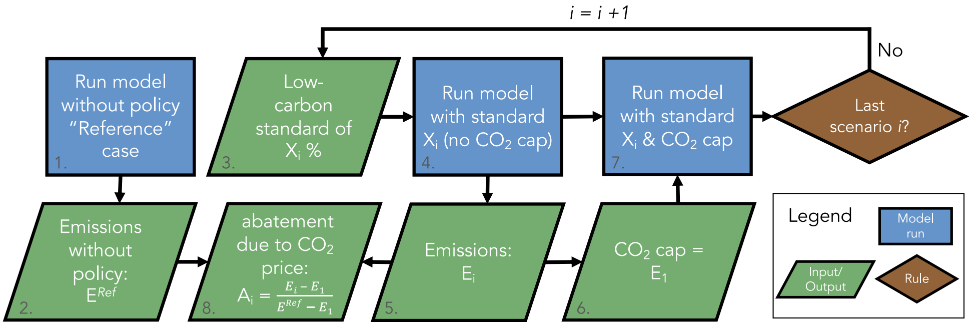

Fig. 2. Experimental procedure for generating policy mixes. Process is applied with each model separately. For the EPPA model, "run model without policy" refers to the model's "Paris Forever" scenario, which assumes no policy additional to commitments under the Paris Agreement.

explore different mechanisms behind the impacts of policy mixes (they are compared further in Section 4).

Three types of low-carbon standards are evaluated: a Clean Energy Standard (CES), which requires a given share of electricity to be sourced from clean technologies; a Renewable Portfolio Standard (RPS), which resembles a CES but is restricted to renewable technologies; and a transportation standard, modeled after the U.S. Corporate Average Fuel Economy (CAFE) standards, which 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).

2.2.1. Experimental design

The experimental procedure seeks to quantify how the cost of a policy mix varies as the policy mix trades off emission reductions from one policy with emission reductions from another policy. Three features distinguish this procedure: it models two policies at once, it generates alternative combinations that vary the shares of total emission reductions contributed by each policy, and it enforces an apples-to-apples consistency between all combinations by maintaining a constant amount of overall emission reductions.

The experimental procedure is illustrated in Fig. 2. We first run each model to generate a Reference case meant to represent a "business as usual" scenario in the absence of policy (step 1 in Fig. 2), which allows us to derive reference emissions denoted E^{Ref} (step 2). Next, we select a given low-carbon standard policy (step 3) of a given stringency (for example, a 100% Clean Energy Standard), which can be denoted X_1 in the first iteration of the algorithm, i.e. the first element of a vector of pre-defined stringencies X_i (the stringencies are shown in the third column of Table 1). We then run the model (step 4), and derive CO2 emissions (step 5) denoted E_i. Next we introduce a carbon constraint that caps CO_2 emissions (step 6) at the level achieved by the standard (in the first iteration of step 5), or E_1. We then run the model again with both the standard and the carbon constraint (step 7). The experiment proceeds by repeating steps 3, 4, 5, and 7 for lower and lower standard stringencies (indexed by i). Note that there are two sets of model runs for all standard stringencies i (corresponding to steps 4 and 7): one with only the standard (leading to emissions E_i) and one with both policies (where emissions are always E_1, i.e. the cap). The second set of model runs (step 7) generates the full spectrum of climate policy mixes from a standard-only policy to a pricing-only policy, with all combinations achieving the same emission level, E_1 (all policy mixes are shown in the third column of Table 1). The first set of model runs (step 4) is necessary for quantifying the reliance of a policy mix on a given policy, which is a key feature of our analysis. We define reliance as the share of abatement caused by a given policy. We denote abatement caused by carbon pricing in each scenario as A_i and estimate it using: $A_i = \frac{E_i - E_1}{E^{Ref} - E_1}$ (step 8 in Fig. 2). In other words, we quantify the abatement caused by carbon pricing as the amount of emissions that would have occurred without the cap. This is the value shown on the bottom x-axis in the left panels of Figs. 3 and 7. Conversely, the abatement share of the standard in each scenario is $1 - A_i$ (shown on the top x-axis of the mentioned figures).

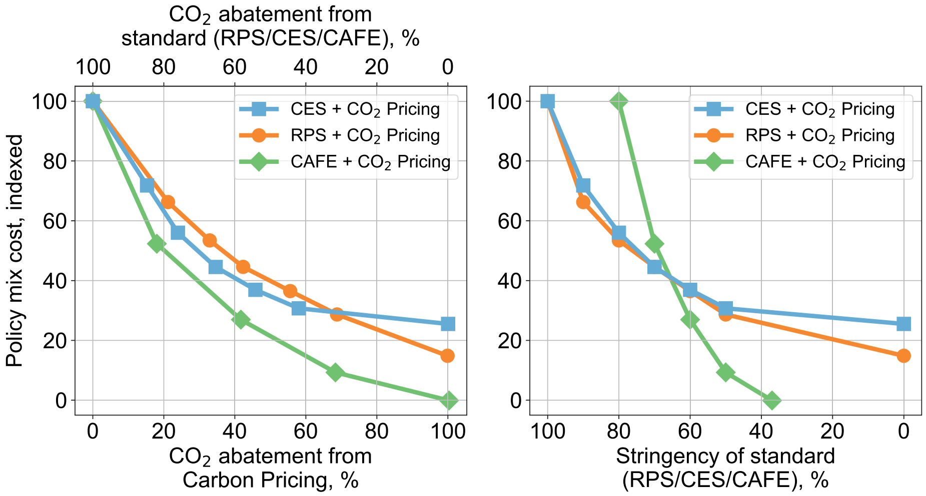

Fig. 3. Costs of alternative climate policy mixes modeled in EPPA. Each marker represents a policy mix scenario. All policy mixes on a given curve reduce the same amount of CO_2. "Policy cost" refers to the decrease in macroeconomic consumption relative to the Reference case. All policy costs have been 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). RPS: Renewable Portfolio Standard; CES: Clean Energy Standard; CAFE: Corporate Average Fuel Economy standard. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Scenario descriptions.

Model	Policy mix	Scenarios	Policy mix emission reductions
EPPA	RPS + economy-wide carbon pricing	RPS 100% + CO_2 Pricing RPS 90% + CO_2 Pricing RPS 80% + CO_2 Pricing RPS 70% + CO_2 Pricing RPS 60% + CO_2 Pricing RPS 50% + CO_2 Pricing RPS 0% + CO_2 Pricing	Equivalent to reductions achieved by 100% RPS
	CES + economy-wide carbon pricing	CES 100% + CO_2 Pricing CES 90% + CO_2 Pricing CES 80% + CO_2 Pricing CES 70% + CO_2 Pricing CES 60% + CO_2 Pricing CES 50% + CO_2 Pricing CES 0% + CO_2 Pricing	Equivalent to reductions achieved by 100% CES
	CAFE + economy-wide carbon pricing	CAFE 80% + CO_2 Pricing CAFE 70% + CO_2 Pricing CAFE 60% + CO_2 Pricing CAFE 50% + CO_2 Pricing CAFE 37% + CO_2 Pricing	Equivalent to reductions achieved by 80% CAFE
GenX	RPS + electricity carbon pricing	RPS 100% + CO_2 Pricing RPS 95% + CO_2 Pricing RPS 90% + CO_2 Pricing RPS 80% + CO_2 Pricing RPS 0% + CO_2 Pricing	Equivalent to reductions achieved by 100% RPS
	RPS + economy-wide carbon pricing	RPS 100% + CO_2 Pricing RPS 95% + CO_2 Pricing RPS 90% + CO_2 Pricing RPS 80% + CO_2 Pricing RPS 0% + CO_2 Pricing	Equivalent to reductions achieved by 100% RPS

The third column lists the scenarios run for each policy mix. The carbon price in each scenario is generated by the model, and rises as the standard % is reduced. Each scenario relates to one line marker in Fig. 3 for the EPPA model and Fig. 7 for the GenX model. All scenarios for a given policy mix reduce the same amount of emissions, which is indicated in the fourth column. RPS: Renewable Portfolio Standard; CES: Clean Energy Standard; CAFE: Corporate Average Fuel Economy standard.

We propose that the marginal efficiency benefit of pricing diminishes with the extent to which a policy mix relies on pricing for abatement, or A. This leads to the following proposition.

Proposition 2. $\frac{\partial^2 W^*}{\partial A^2} \leq 0$. *That is, welfare improvement from relying more and more on carbon pricing exhibits diminishing marginal returns.*

The second proposition is tested numerically with the two energy system models. We also test it numerically with the theoretical model, and show that it holds for various model parameterizations in the Supplementary document.

The experimental procedure is run for multiple types of policy mixes. Each type of mix combines one type of low-carbon standard with carbon pricing. Note that the different types of mixes achieve different emission reductions (which are determined by the standard being modeled and are indicated in the fourth column in Table 1).

For the experiments, we define welfare improvement as a reduction in policy cost. This cost is computed differently depending on the model used. When using EPPA, we estimate policy cost as the decrease in aggregate macroeconomic consumption (summed across all years and discounted at a rate of 2%; our main results are not sensitive to the exact discount rate) resulting from a given policy mix, relative to consumption under the Reference case. When modeling with GenX, policy cost represents the increase in electricity system cost resulting from a given policy mix relative to electricity system cost in the Reference case. For a sensitivity test using less stringent climate policies, see the Supplementary document (Section 2.1).

2.2.2. Energy system models

The version of EPPA used here was described by Ghandi and Paltsev (2020). As a Reference case, we use the "Paris Forever" scenario, which assumes implementation of commitments under the Paris Agreement and no additional policy after 2030. We then 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 standards. 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 Reference case includes a CAFE standard, which mandates a 37% improvement in average fuel efficiency by 2040 relative to 2015 consistent with the Paris Forever scenario by Ghandi and Paltsev (2020). 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 modeled as described by Karplus and Paltsev (2012). In EPPA, this standard encourages improvement in fuel efficiency, reduction in gasoline-fueled miles traveled, or adoption of cleaner technologies such as hybrids or battery-electric vehicles. All policy scenarios are listed in Table 1.

The GenX model used in this paper is the version parameterized and configured by Dimanchev et al. (2021) 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 h 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 case, we model the system without any climate policy.[1] 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 carbon pricing.

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 approximately \$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. Our 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.

3. Results

3.1. Theoretical results

We provide an analytical proof of Proposition 1, which states that the efficiency benefit of carbon pricing exhibits diminishing marginal returns as the role of the standard in the policy mix is reduced, or $\frac{\partial^2 W^*}{\partial \sigma^2} \leq 0$. The proof relies on the observation that, at the optimal point, the two policy constraints bind such that: $\frac{q_L}{(q_H+q_L)} = \sigma$ and $q_H \beta_H + q_L \beta_L = c$. These equations allow us to express how the optimal quantities of both products depend on the stringency of the standard σ: $q_H := F(\sigma) = \frac{c(1-\sigma)}{\beta_H(1-\sigma)+\sigma\beta_L}$; and $q_L := G(\sigma) = \frac{c\sigma}{\beta_H(1-\sigma)+\sigma\beta_L}$. The optimal welfare W^* can therefore be expressed as a function of the standard: $W(\sigma) = U(F(\sigma), G(\sigma)) - C_H(F(\sigma)) - C_L(G(\sigma))$. Differentiating this function with respect to σ (see Appendix A.1) confirms that $\frac{\partial W^*}{\partial \sigma} < 0$ for all points where the slope of the welfare function is larger than the slope of the cap-and-trade constraint (i.e. between points A. and B. in Fig. 1). Deriving the second derivative Appendix A.2 confirms that $\frac{\partial^2 W^*}{\partial \sigma^2} < 0$, proving Proposition 1.

Numerical experiments with the theoretical model further demonstrate both Propositions 1 and 2 for various parameterizations (see Figures S1 and S2 respectively in the Supplementary document).

3.2. Economy-wide modeling with EPPA

Fig. 3 displays results derived from EPPA regarding both of our propositions (the left panel relates to Proposition 2, and the right panel relates to Proposition 1). The values on the far left in each panel represent a standard-only climate policy where the carbon price is \$0/tCO_2 (for example, the left-most marker on each blue line represents the "CES 100% + CO_2 Pricing" scenario in Table 1). The values to the right represent gradual trading off of standard policies for carbon pricing (for example, the second marker on each blue line represents the "CES 90% + CO_2 Pricing") scenario.

The non-linearity of the curves in the left panel of Fig. 3 demonstrates Proposition 2 stating that the efficiency benefit of increasing reliance on carbon pricing has diminishing marginal returns. Specifically, we estimate that relying on carbon pricing for 20% of emission reductions (and on a standard for 80%) lowers total cost by 32%, 37%, and 50% for the RPS, CES, and CAFE respectively relative to a standard-only approach (illustrated by the y-axis values corresponding to where the lines on the left panel of Fig. 3 cross the vertical line corresponding to 20% abatement from carbon pricing). These savings are respectively equivalent to 37%, 49%, and 50% of the savings of

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

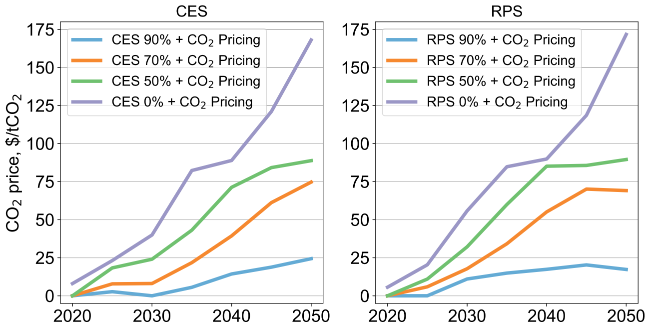

Fig. 4. Carbon price trajectories by policy mix modeled in EPPA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the theoretically optimal pricing-only policy (found by comparing the same places on the curves to the right-most points). This shows that a limited reliance on carbon pricing provides a disproportionately large share of the benefits of the theoretically optimal pricing-only policy. Moving rightward, the marginal savings diminish. Relying equally on both policies for 50% of emission reductions reduces costs by 60%, 65%, and 79% for the RPS, CES, and CAFE respectively. Importantly, this is respectively already 71%, 88%, and 79% as cost-effective as the pricing-only policy (illustrated by comparing the middle of the lines on the left panel to the right-most points).

The right panel of Fig. 3 reflects Proposition 1 stating that the efficiency benefit of pricing decreases at the margin as the role of the standard is reduced. Specifically, we estimate that moving from a 100% CES with a \$0/tCO_2 carbon price to a 90% CES with carbon pricing reduces total policy costs by roughly 28% (as shown by comparing the first and second markers on the blue line in either panel). Costs continue to fall as the standard is reduced, but by a decreasing amount. The RPS and CAFE results similarly show that a modest reduction in the standard in favor of pricing yields a disproportionately large reduction in costs. A policy mix including a 90% RPS and a cap-and-trade (second circle from the left on the orange lines) reduces policy cost by 34% relative to a 100% RPS scenario (first circle on the orange lines). As we move rightward, Proposition 1 continues to hold. 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. The CAFE analysis likewise shows that relying on a 70% reduction standard and a cap-and-trade reduces policy costs by 48% (second green diamond in the right panel) relative to an 80% standard with a \$0/tCO_2 carbon price. Costs decrease dramatically in the final scenario (featuring a 37% CAFE) to 1% of the costs of the 80% CAFE.

Fig. 4 presents the carbon price trajectories for different policy mixes. These results further show how the carbon prices in many of our scenarios are relatively modest. To relate this figure to our previous results, note that the first line (in blue) in the left panel ("CES 90% + CO_2 Pricing") refers to the scenario represented by the second markers on the blue lines in Fig. 3; the second line in Fig. 4 (in orange) represents the fourth markers, and so on. The right panel relates to the corresponding scenarios for the policy mix containing an RPS in Fig. 3. The Supplementary document further illustrates the relationship between policy mix cost and the carbon price across policy mix scenarios (Figure S4).

3.2.1. Sources of abatement by policy mix

The cost reductions caused by incorporating carbon pricing in climate policy can be partly explained by the availability of cheaper CO_2 abatement options outside of the scope of the standard. Fig. 5 illustrates emission reductions by sector for each of the policy mixes 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 unintended second-order effect of emissions leakage from one sector to another, visible in Fig. 5. 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 the use of fossil fuels for residential energy.

3.2.2. Shadow carbon values for policy mixes

To further explain the results, we calculate the shadow carbon value of the RPS and CES constraints, expressed in dollars per ton of abatement[2] (Fig. 6). 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 Fig. 6 plots these calculations for all policy mix scenarios (each marker represents a scenario). In the right panel, we report the carbon price generated by the cap-and-trade policy across the policy mixes.

The results displayed in Fig. 6 show how the marginal costs of RPS and CES policies rise very steeply as the standards approach 100% stringency. 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 the marginal cost of the CES increases considerably beyond 90%. The marginal cost of the RPS at 80% exceeds \$2,200 per ton; and 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 underscore the important contribution of carbon pricing to keep down the cost of deep decarbonization goals. The marginal cost of relying almost exclusively on the modeled standards for deep decarbonization goals is relatively high. Carbon pricing can keep society from traveling up the steepest part of the RPS or CES marginal cost curve, yielding substantial efficiency gains.

3.3. Electricity system modeling with GenX

The use of GenX in this paper is intended to test the extent to which our previous findings hold under a more detailed representation of the electricity sector specifically. The only type of low-carbon standard we present is an RPS. We do not show results for a CES because our GenX implementation does not distinguish between a 100% CES and a CO_2 cap of zero (both policies limit the model to zero-carbon technologies and there is no possibility for energy efficiency).

Fig. 7 displays how policy costs vary across different combinations of RPS and carbon pricing modeled using GenX (the left panel illustrates Proposition 2, and the right panel illustrates Proposition 1). Consistent with our previous results, we find that the increased cost-effectiveness of relying more on carbon pricing exhibits diminishing marginal returns (as illustrated by the non-linearity of the curves).

As shown by the left panel in Fig. 7, we estimate that relying on carbon pricing for 20% of emission reductions lowers total cost by 45% and 57% for the electricity and economy-wide pricing respectively

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[2] 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.

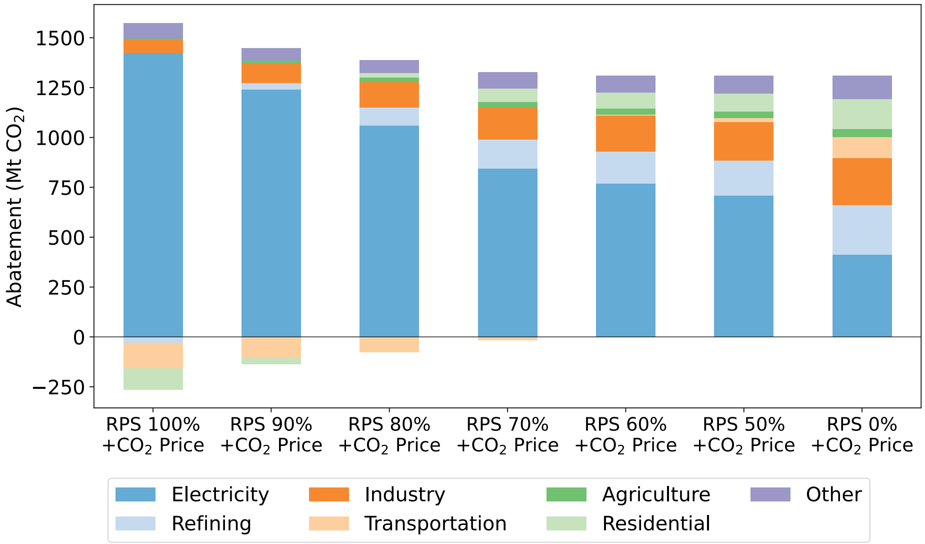

Fig. 5. CO_2 abatement by sector for alternative climate policy mixes. All policy mixes reduce the same amount of CO_2.

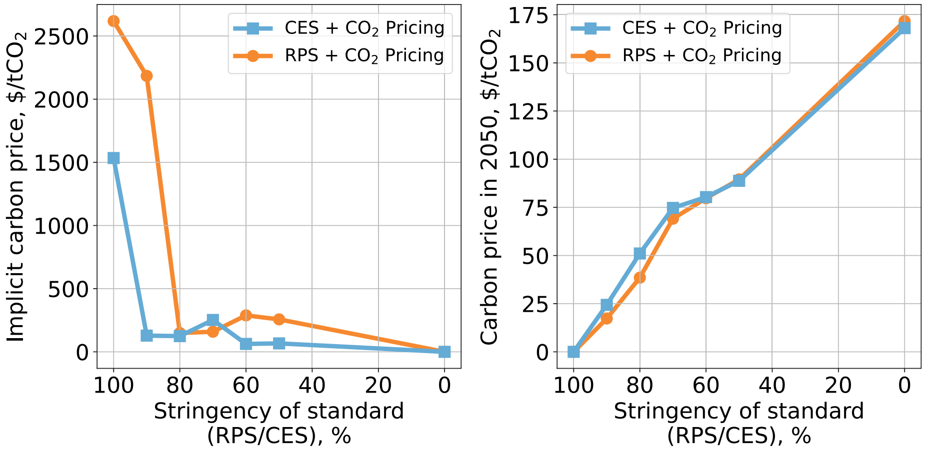

Fig. 6. Shadow carbon values by policy across policy mix scenarios. All policy mixes on a given curve reduce the same amount of CO_2. The implicit carbon price (left panel) is the marginal cost of the standard constraint calculated by relaxing the constraint by 2% and estimating the ratio of the reduction in social costs to the increase in emissions.

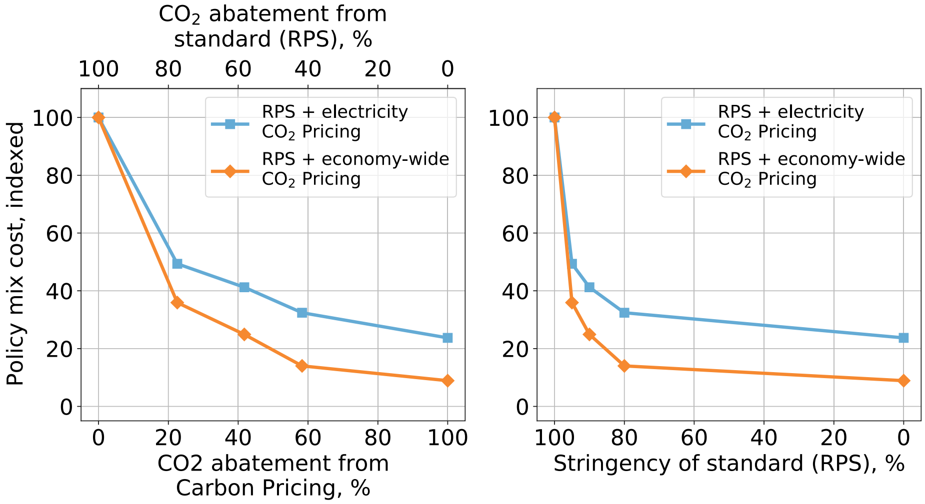

Fig. 7. Costs of alternative climate policy mixes modeled in GenX. Each marker represents a policy mix scenario. All policy mixes on a given curve reduce the same amount of CO_2. “Policy cost” refers to the increase in total electricity system costs from the Reference case without policy. System costs comprise the cost of: investment, generation, demand shifting, storage, demand curtailment, and starting of thermal plants. RPS: Renewable Portfolio Standard. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

compared to a standard-only policy (as illustrated by the *y*-axis values corresponding to where the lines on the left panel of Fig. 7 cross the vertical line corresponding to 20% abatement from carbon pricing). These savings are equivalent to 59% and 62% respectively of the savings of the theoretically optimal pricing-only policy (found by comparing the same places on the curves to the right-most points). Consistent with previous results, this shows that a partial reliance on pricing provides a disproportionately large share of the benefits of the theoretically optimal pricing-only policy. Relying equally on both a standard and pricing for 50% of emission reductions reduces costs by 63% and 81% respectively. Importantly, this is respectively already 83% and 88% as cost-effective as the pricing-only policy. Cost reductions from increasing reliance on carbon pricing are driven in the GenX model by the use of cheaper zero-carbon technologies that are otherwise assumed ineligible for the RPS. In particular, relaxing the RPS leads to the use of gas with CCS (we assume a 100% CO_2 capture rate for simplicity). This allows the system to reduce the so-called "oversizing" of variable renewables (Sepulveda et al., 2018), which in our model is the primary driver behind the non-linear increase in policy costs associated with high renewable penetration.

Fig. 7 further displays how policy mix costs vary across different standard stringencies (right panel). A policy mix that a includes a 95% RPS and an electricity cap-and-trade reduces costs by 51% relative to the 100% RPS (shown by the second blue square from the left in the right panel). The RPS 90% scenario reduces costs by 59% relative to the 100% RPS (third blue square in the right panel). We find similar results under our economy-wide cap-and-trade scenario (orange line in Fig. 7). A policy mix that includes a 95% RPS and an economy-wide cap-and-trade reduces costs by 65% relative to the 100% RPS (shown by the second orange diamond from the left in the right panel). In this scenario, only 23% of the emission reductions are driven by the cap-and-trade policy (left panel).

4. Discussion and conclusions

This paper explores how individual climate policies should be combined into a policy mix. Past research focused on how individual policies perform when implemented separately. In contrast, we assess the full spectrum of possible combinations of two popular types of climate policies. In this way this paper contributes to the study of policy mix design, in line with Tinbergen's (1952) call for designing economic policy as a "coherent entity". We do this by extending previous theory and introducing a new experimental procedure for evaluating policy mixes numerically. This work thus contributes a quantitative approach to assessing climate policy mixes, extending the qualitative frameworks introduced in past work (Grubb et al., 2017; Rosenow et al., 2017; van den Bergh et al., 2021), and complementing other quantitative frameworks for designing carbon pricing as one component within policy portfolios (Kaufman et al., 2020).

We first show that, in line with prior work, increasing the reliance of a policy mix on carbon pricing increases the cost-effectiveness of the mix (i.e. efficiency). For example, the combined results from both energy system models show that relying on carbon pricing for 20% of emission reductions (and on a standard for 80%) already reduces policy mix cost by 32%–57% (equivalent to 37%–62% of the total savings delivered by the theoretically optimal pricing-only policy). Note that the magnitude of this result is dependent on the experimental design (namely, the specific policies we choose to compare and the fact that we do not consider multiple standards at once, which we elaborate on in the last paragraph). Rather than estimate the cost savings from pricing, this paper's main goal is to shed light on how the marginal cost savings change (the shape of the curve in Figs. 3 and 7). The main contribution of this paper is to show that the improvement in cost-effectiveness diminishes the more a policy mix relies on carbon pricing (as opposed to a standard). Our results show that, for example, relying on pricing and standards equally for 50% of emission reductions reduces costs by 60%–81% (a smaller marginal gain than the estimate mentioned above associated with pricing equivalent to 20% of abatement). Importantly, this is also already 71%–88% as cost-effective as the theoretically most cost-effective pricing-only policy. This finding shows that carbon pricing follows a Pareto principle (Pareto, 1906): modest carbon pricing delivers a disproportionately large share of the advantage of the theoretically optimal pricing-only policy.

Several implications for policy making follow. First, complementing stringent standards with modest carbon prices would reduce policy costs substantially. Second, partial standards result in a relatively small increase in total policy cost, which may be outweighed by their benefits (which we do not quantify here). More generally, this suggests that there are many "near-optimal" climate policy mixes for policy makers to choose from. While a pricing-only climate policy has been traditionally seen as theoretically ideal, deviations from this "optimum" may be justified if they deliver on other societal criteria that outweigh the modest additional costs. For example, renewable support policies such as standards have been motivated by knowledge spillover effects and energy security (Borenstein, 2012; Lehmann and Gawel, 2013). Our findings extend the emerging literature highlighting the possibilities for practical "near-optimal" options in energy systems (DeCarolis et al., 2017; Neumann and Brown, 2021). Overall, our results lend support to combining both standards and pricing, which could offer a pragmatic way forward for future policy making that balances the advantages of each policy.

For specific jurisdictions, the implications of our main finding (regarding the diminishing marginal benefits of relying on pricing) differ depending on where on the policy mix spectrum they are. For governments relying purely on very stringent standards with limited sectoral scope, the result suggests some pricing could offer substantial efficiency benefits. For jurisdictions that already rely on both policies, increasing reliance on pricing at the expense of standards may not be justified given the potentially limited gains in efficiency. Additional analysis in the form of impact assessment with more detail specific to a given jurisdiction and its policy mix is required to guide decision making.

The explanations for our main finding vary between our analytical and energy system modeling approaches because the models explore different mechanisms. The analytical 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: specifically, by discouraging over-consumption of the low-carbon product (a mechanism which is not present in the energy system models). This was explained in detail by Holland et al. (2009). Our contribution is to show that this effect diminishes at the margin due to the non-linear relationship between welfare and consumption. We further show how this effect is influenced by key model parameters (see Supplementary Material).

The energy system modeling using EPPA and GenX illustrates the trade-off between a low-carbon standard limited to one sector or a set of technologies and a broader carbon price (economy-wide in EPPA and GenX or a technology-neutral electricity carbon price in GenX). These results illustrate the already well-established idea that carbon pricing provides a cost-saving advantage by incentivizing a broad set of low-cost CO_2 abatement options. The novel aspect of our work is to show that these benefits exhibit diminishing marginal returns, which appears intuitive but had not been tested or quantified before to our knowledge. Our results further show that another potential mechanism behind the initially large marginal efficiency benefit of carbon pricing is the prevention of unintended second-order effects, whereby stringent standards in one sector (such as electricity) cause higher emissions in other sectors (such as transport and residential energy).

A number of limitations affect the applicability of this analysis. In practice, the choice of a policy mix would require understanding both the marginal benefit and the marginal cost of relying on a given policy instead of another (where reliance is defined as the share of abatement caused by the policy). Our paper focuses on a smaller version of this problem to illustrate the concept, facilitate clarity, and allow for necessary tractability. While we focus on the two-policy case of choosing a mix combining a standard and carbon pricing, government policy often combines more instruments. In this case, the quantitative impact of increasing reliance on carbon pricing may differ substantially from our estimates, and this would depend on the exact policy mix under consideration. Specifically, if governments combine multiple standards at the same time, this would leave fewer cheap abatement options for an economy-wide carbon price to incentivize and would thus likely reduce the efficiency gains relative to what we estimate. Another limitation is that we only consider the marginal efficiency benefit of trading off standards for pricing. To choose an optimal combination, policy makers would also have to quantify the marginal costs of trading off standards for pricing, which relate to the distinct advantages of standards such as political feasibility, knowledge spillovers, and energy security. Also excluded from our analysis are other popular climate policies such as clean technology subsidies. Another limitation is that we do not test any sequential staging of climate policies, which is an important area for future work (Goulder, 2020). Overall, this work is not a comprehensive analysis of the optimal policy mix in a given jurisdiction, but a step toward a quantitative understanding of policy mix choices.

CRediT authorship contribution statement

Emil Dimanchev: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Christopher R. Knittel:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This research was funded by MIT's Center for Energy and Environmental Policy Research (CEEPR), which is supported in part by a consortium of industry and government Associates. The list is available at: http://ceepr.mit.edu/support/associates.

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Appendix A. Analytical proof of Proposition 1

The following presents the detailed proof of Proposition 1, which states that $\frac{\partial^2 W^*}{\partial \sigma^2} < 0$. The next subsection derives the first derivative of W with respect to $sigma$, and the following subsection derives the second derivative.

A.1. The efficiency benefit of carbon pricing

First, we set out to confirm 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, this idea states that $\frac{\partial W^*}{\partial \sigma} < 0$.

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

$$\begin{aligned}\frac{\partial W^*}{\partial \sigma} &= \frac{\partial U}{\partial F}\frac{dF}{d\sigma} + \frac{\partial U}{\partial G}\frac{dG}{d\sigma} - \frac{\partial C_H}{\partial F}\frac{dF}{d\sigma} - \frac{\partial C_L}{\partial G}\frac{dG}{d\sigma} \\ &= \frac{dF}{d\sigma}\left(\frac{\partial U}{\partial F} - \frac{\partial C_H}{\partial F}\right) + \frac{dG}{d\sigma}\left(\frac{\partial U}{\partial G} - \frac{\partial C_L}{\partial G}\right)\end{aligned}$$

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 Fig. 2 in the main manuscript). 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 Fig. 2 in the main manuscript). 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 Fig. 2 in the main manuscript, 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: $\frac{\partial W^*}{\partial \sigma} < 0$.

A.2. Diminishing marginal efficiency benefit of carbon pricing

The main proposition of this paper 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:

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

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.[3]

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106697.

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[3] 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.

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