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Abstract

Despite the global nature of climate change, carbon pricing is driven by regional and sectoral carbon taxes or trading programs, each with unique features and disparate marginal costs. Linking these fragmented regional or sectoral programs could improve environmental and economic outcomes, but differing initial conditions pose a challenge to linking. We explore the use of an allowance exchange rate, which denominates the compliance value of an emissions allowance differently in each program. In a theoretical model, we find that linking with an exchange rate in the politically plausible range—between traditional 1:1 trading (without an exchange rate) and the autarky price ratio—yields lower total abatement costs and greater economic surplus in each region, compared to autarky. Linking in this range also achieves greater emissions abatement than the (equal) amount achieved at each bookend. For this reason, 1:1 linking, which achieves a uniform allowance price and marginal cost, is nonetheless rarely socially optimal. When program caps achieve inefficiently low abatement, it would be welfare-improving to link at an exchange rate that increases total abatement in the linked system, so the socially optimal exchange rate lies within the politically plausible range. We further illustrate these results, and identify additional outcomes of interest to policymakers, using a simulation model of electricity markets.

Key Words: greenhouse gas, climate change, climate policy, carbon market, policy coordination

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1. Introduction

The environmental consequences of greenhouse gas emissions are felt around the globe, regardless of where those emissions originate. Correspondingly, in the 1990s, numerous economists heralded a single international carbon market as the cost-effective solution to climate change. Such a market would, in principle, lead to a single global carbon price through the trade of emissions allowances, which would serve to identify and realize emissions reductions at the lowest possible cost and yield the cost-effective geographic distribution of abatement. Despite the logic of this approach, international policymakers were unable to implement this vision and climate governance has taken a different path. Today 64 international, national, regional, state, provincial and municipal carbon pricing or trading programs are in operation, instead of the single international carbon market that was once imagined (World Bank 2021). Additionally, in some jurisdictions, different sectors of the economy are covered by separate existing or proposed pricing or trading programs (Perino, Ritz, and van Bentham 2020).[1] This fragmentation leaves important opportunities for improved cost-effectiveness on the table and coordination could enable greater environmental stringency at lower total costs.

A central way to improve the cost-effectiveness of this patchwork is to aggregate through bilateral or multilateral linking, a process in which the regulatory authorities in each program mutually allow their regulated firms to use emissions allowances from any of the linked jurisdictions to meet compliance obligations (Jaffe, Ranson, and Stavins 2009).[2] The expected cost savings in linking carbon markets stem from differences in marginal abatement costs, but linking markets with different emissions reduction opportunities will create a revenue transfer that is viewed as politically challenging (Verde et al. 2020). Recent policy discussions regarding the linking of trading programs have considered an allowance exchange rate, which potentially denominates the compliance value of an emissions allowance (i.e., the quantity of emissions per

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[1] For examples of overlapping sectoral programs, see https://climate-xchange.org/regional-cap-and-invest/ and https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3542.

[2] We primarily focus on bilateral links, although a variety of other linking types exist, including incremental alignment of carbon policies, which Burtraw et al. (2013) refer to as "linking by degrees", unilateral linking, various forms of restricted links (Mehling and Haites 2009; Schneider et al. 2017), and multilateral linking (Doda, Quemin, and Taschini 2019).

allowance) differently in each program. An exchange rate provides policymakers with a mechanism to better balance the costs and benefits of linking within one's jurisdiction, which we discuss in detail below, and to reconcile different program characteristics that otherwise might prohibit programs from linking. An exchange rate also provides policymakers with a way to link separate sectoral programs in the same jurisdiction without fully harmonizing the programs.

In this paper, we examine how an allowance exchange rate may be used to improve both the environmental outcome of a linked system and the economic outcomes in each linked region or sector, as well as to harmonize trading programs with different initial program conditions including marginal costs, program stringency, and price collars. We develop an analytical model of a linked trading system to describe how an exchange rate affects overall efficiency and market outcomes, including distributional effects. We further explore these results by simulating the linking of two trading programs using a detailed model of regional electricity markets within the US that characterizes different specific design features in each program, accounting for how they interact with their respective regional electricity markets.

Our analytical model yields novel and non-intuitive results about linking trading programs with an exchange rate. We first find that linking with an exchange rate between traditional 1:1 trading (without an exchange rate) and the autarky price ratio yields greater abatement than the (equal) amount achieved at each of the bookends and at strictly lower abatement costs than autarky. This range of exchange rates is also the most plausible to be used by policymakers. Following from this result, we show that traditional linking (i.e., one-for-one trading between programs) with fully fungible allowances, which achieves an efficient distribution of abatement through a uniform allowance price, is rarely socially optimal. Trading programs often fail to set emissions caps at optimal levels and linking with an exchange rate can alter the total amount of abatement, because one allowance no longer corresponds to one unit of emissions. As a result, it is socially optimal to use an allowance exchange rate that trades off the efficiency of equating marginal costs in favor of moving the linked system closer to the efficient level of total abatement. When trading program caps achieve an inefficiently low level of emissions abatement, this socially optimal exchange rate lies within the politically plausible range. We also show that exchange rate values in this range yield economic surplus gains in each region, as compared to autarky. Thus, a well-designed linked system can yield benefits for the environment and each regional economy. We further show that an exchange rate can interact in complex ways with price containment mechanisms. In some cases, price collars may restrict a linked system from achieving the optimal outcome. In other cases, however, an exchange rate may allow for a link that would otherwise be infeasible because of incompatible price collars.[3]

Our simulation modeling explores the linking of two hypothetical trading programs that cover regions of the United States electricity sector. Using this more robust modeling framework, we confirm our analytical results about abatement, abatement costs, and the socially optimal allowance exchange rate. We find, however, that the efficiency gains may be distributed in ways not predicted by theory. Additionally, linking with an exchange rate can greatly affect the co-benefits of reducing other air pollutants, which can alter both the efficiency gains and the political economy of linking.

A wealth of qualitative literature describes the potential advantages of linking in economic terms and the institutional arrangements that would be necessary under international agreements (Mehling, Metcalf, and Stavins 2018). For example, in principle, bilateral or multilateral linking achieves a unified price per unit of carbon dioxide (CO_2) emissions across the newly linked system that is expected to lower overall abatement costs. The potential gains from efficiently allocating abatement are greater the greater are differences in pre-linked allowance prices. Linking also can dampen allowance price volatility caused by regional variations in the demand or supply of allowances because typically the factors that influence emissions such as weather or economic activity are imperfectly correlated across jurisdictions (Flachsland, Marschinski, and Edenhofer 2009; Burtraw et al. 2013; Doda, Quemin, and Taschini 2019). In some circumstances, linking can ameliorate concerns over competitiveness impacts by explicitly addressing the possibility for leakage of economic activity between jurisdictions that may result from differences in program stringency (Jaffe, Ranson, and Stavins 2009). Moreover, there are other potentially significant benefits to linking that are not economic in nature. From an environmental perspective, the reduction in abatement costs achieved by linking could make it easier to enhance ambition (Bodansky et al. 2016). From a political perspective, linking starts to dispel the free-rider narrative that can prevent individual jurisdictions from pricing carbon in the absence of an international carbon price (Flachsland, Marschinski, and Edenhofer 2009).

There is also a significant qualitative literature that outlines the potential costs of linking. First and foremost, established links between trading programs have required significant negotiations between jurisdictions to harmonize the design of the programs; the time and resources

[3] Vivid Economics (2020) provides a detailed discussion of linking emissions trading programs with market stability measures and calls for price collars to be aligned before linking. We show an exchange rate can be used to effectively align these price collars without directly changing the price floor or ceiling in either trading program.

spent on this process of harmonization can be thought of as a fixed cost of linking. In addition, the efficiency gains achieved by linking may come with associated costs. For example, linking requires ceding some control over domestic allowance prices, which might be regarded as a political cost (Ranson and Stavins 2016), or a virtue when it insulates policymakers from narrow interest groups within their jurisdiction (Burtraw et al. 2013). While linking may reduce overall abatement costs, it may have negative economic impacts on particular actors in each jurisdiction (Newell, Pizer, and Raimi 2013).[4] Moreover, linking can exacerbate allowance price volatility in certain cases (Doda and Taschini 2017). From an environmental perspective, a broader market is likely to reduce leakage, but linking could increase emissions leakage if allowance prices increase in the program that is more susceptible to leakage (Jaffe, Ranson, and Stavins 2009) and may alter incentives for cap setting, encouraging programs to set higher emissions caps to achieve lower prices and therefore export more allowances, thereby resulting in higher emissions than would occur without linking (Bohm 1992; Helm 2003). Weitzman (2019) refers to the former issue as the primary free-rider problem and describes elements of program design including price floors and ceilings to affect distributional outcomes as a potential secondary free-rider problem. Strategic considerations may influence the decision about how to initially distribute emissions allowances, for example, through the use of output-based allocation to provide a production incentive to mitigate leakage that would likely increase the allowance price (Burtraw et al. 2017). Linking also might provide an incentive to introduce companion policies, such as technology support policies, that reduce local demand for allowances, to increases allowance exports and associated government revenues.

Weighing the advantages and disadvantages of a specific link requires an accounting of the unique designs of each of the involved trading programs and how they would interact under a particular linking architecture. Quantitative approaches are useful in this regard. One vein of the quantitative literature on linking utilizes models to provide estimates of the efficiency gains achieved by linking (Springer 2003) or the emissions outcomes of different coalitions of linked trading systems (Paltsev 2001). A second vein of the quantitative literature on linking takes an analytical approach to investigate the impact of different linking architectures (e.g., a link between mass and rate-based trading programs or a restricted one-way link that discounts incoming

[4] In jurisdictions where allowance prices increase due to linking, compliance entities or consumers who purchase goods from these entities will experience greater costs. Conversely, in jurisdictions where allowance prices decrease due to linking, any agent holding excess permits will experience a reduction in the value of these assets and governments will receive less revenue from allowance auctions.

allowances) (Fischer 2003; Schneider et al. 2017), or the impacts of unique program design features (e.g., market size) on the economic implications of linking (Doda and Taschini 2017).

Jurisdictions considering a potential link have some control over the domestic costs and benefits of the link by using an allowance exchange rate, which denominates the compliance value of an emissions allowance (i.e., the quantity of emissions per allowance) differently in each program. That is, an exchange rate mandates that an allowance from one program is worth more or less, in terms of compliance (allowable tons per allowance), than is an allowance from another program. While economists typically discuss exchange rates in the context of pollutants that impose local damages that vary by the source of emissions (Hung and Shaw 2005), the scholarly interest in applying exchange rates in the context of greenhouse gas emissions has increased in recent years (Fischer 2003; Metcalf and Weisbach 2012; Holland and Yates 2015; Böhringer and Fischer 2020). Greenhouse gas allowance exchange rates have also been included in recent policy discussions, including efforts by the World Bank's Networked Carbon Market Initiative[5] (Marcu 2015; Macinante 2016) and China's stated intentions to discount allowances from regional emissions markets when its national trading program launches (Carbon Pulse 2016).[6] In addition, a discount rate—which is effectively an "asymmetric" exchange rate—is being negotiated under Article 6 of the Paris Agreement to achieve overall mitigation in global emissions (Schneider et al. 2018; Piris-Cabezas and Lubowski 2019). A fluctuating exchange rate may emerge implicitly in programs linking jurisdictions with different monetary currencies if at least one has a binding price collar, such as the California-Quebec link. Quemin and de Perthuis (2019) and Schneider et al. (2017) compare exchange rates with other mechanisms, such as quantitative limits on trading and border adjustments as transitional mechanisms, to guide heterogeneous programs towards cost-effective outcomes. Linking with an explicit exchange rate would involve accounting for the jurisdiction of origin in allowance portfolios in allowance exchanges and portfolios, which incidentally may offer an administrative remedy to some of the challenges of potential de-linking (Pizer and Yates 2015).

Where carbon pricing already exists in segments of the economy, many jurisdictions are considering new and separate programs in other sectors. The motivation for separate programs is that the price elasticity of emissions reductions is relatively low, for example in the transportation

[5] The World Bank's Networked Carbon Market Initiative is focused on facilitating cross-border allowance trades based on a shared understanding of the relative value of different actions, instead of "harmonizing" climate actions so that units can be traded on a one-to-one basis.

[6] See also https://icapcarbonaction.com/en/ets-map?etsid=55.

and building sectors, and a uniform carbon price linking to existing programs would impose a cost burden in those new sectors without yielding substantial investment or emissions reductions. Nonetheless, carbon pricing can accelerate diffusion of technology and provide revenue to fund infrastructure and other investments. Even within existing regional programs, the ambitions of individual jurisdictions often evolve differently over time. Many jurisdictions have mandated accelerated emissions reductions even while they are linked within a broader regional market, which could result in emissions leakage within the broader market. Linking sectors or jurisdictions that have different ambition and abatement opportunities using an exchange rate can improve cost effectiveness while attenuating distributional concerns and financial flows among sectors or programs.

Both the qualitative and quantitative veins of the literature are useful in characterizing the theoretical benefits and costs of linking but tend to assume that trading programs are nearly identical in design. We extend the existing literature by evaluating the linking of regional and sectoral trading programs with various and different designs (i.e., different levels of program stringency and price collars) and considering how different design parameters interact with alternative architectures for linking (e.g., different exchange rates for allowances). We make two primary contributions with this work. First, we develop an analytical model that formalizes the economic implications and emissions market outcomes of regional or sectoral linking with an exchange rate. With this model, we are the first to analytically describe the linking of sectoral trading programs. The model yields novel findings on the results of linking emissions markets, as well as the formalization of results that had previously been described only qualitatively. Second, we test several of our analytical results and illustrate other important market outcomes of linking by simulating a link between regional trading programs. We use a simulation model of electricity markets within the US to characterize the specific design features of two hypothetical regional trading programs, accounting for how they interact with their respective regional electricity markets. We simulate the trading programs in autarky and under various exchange rates. The electricity market model allows us to illustrate a range of efficiency and distributional implications and emissions outcomes that can arise from linking without losing the detailed designs of the two emissions markets as well as the nuanced and important interactions that might occur between them when linked.

2. Analytical Model of Linking

We model a regional economic sector with production supplied by a representative firm. We first show how this representative firm responds when faced with a policy that imposes a price on CO_2 emissions. We next describe the equilibrium outcomes of regional or sectoral emissions trading programs in two separate markets, which we describe as autarky. We then show how the outcomes change when two emissions markets link through the trade of allowances.[7]

Production

Production within a regional economic sector is characterized by a representative firm that uses a particular production technology and energy to produce a fixed level of output at lowest cost. The cost to the representative firm of producing output is a function of CO_2 emitted during production, E:

$$K(E) = \alpha - \beta E + \frac{\gamma}{2} E^2$$

The parameters α, β, and γ are region- and sector-specific and depend on the quantity of output produced and the firm's production technology. We assume these parameters are fixed over the time horizon considered[8] and further assume they are positive: $\alpha, \beta, \gamma > 0$. With no carbon emissions policy in place, this firm minimizes production cost by emitting $\bar{E} = \frac{\beta}{\gamma}$.

If the firm is subject to an emissions policy that imposes an opportunity cost of p on each unit emitted, the firm deviates from this baseline level of emissions. The additional cost of producing output with fewer emissions is a function of the level of abatement, A, and is given by $C(A) = K(\bar{E} - A) - K(\bar{E})$, which yields:

$$C(A) = \frac{\gamma}{2} A^2$$

Each unit of abatement also reduces the firm's cost of policy compliance by p. When faced with this opportunity cost on emissions, the firm selects the level of abatement that minimizes its total cost:

$$\min_{A} C(A) - pA$$

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[7] We initially only consider an emissions cap, but we later introduce a price collar on emissions allowances. This more general model also applies to the linking of a broader set of carbon pricing policies, such as a carbon tax, which can be interpreted as an emissions trading program with a price floor that is coincident with a price ceiling. Metcalf and Weisbach (2012) consider linking between a cap and trade program and a carbon tax.

[8] Holding these parameters fixed implicitly assumes that productive capital and the level of production are fixed over the time horizon considered. This simplifying assumption corresponds well with the electricity sector, which features long lead times for new capacity and demand that is highly inelastic. Our simulation model also assumes electricity demand and aggregate production are fixed.

This optimization problem yields the first-order condition:

$$\frac{\partial C}{\partial A} = \gamma A = p \tag{1}$$

This is the familiar result that the representative firm's optimal level of abatement equates its marginal abatement cost, γA, to the marginal cost of emissions, p.

Emissions Trading in Autarky

We now consider the specific design of the emissions trading program and the resulting outcomes—abatement, allowance prices, and abatement cost—that occur in this market in autarky. Although an emissions trading policy has many design parameters through which the program can be adjusted, this initial analytical model focuses on only one, and arguably the most important, of these policy parameters: the level of the cap; we later also introduce a price collar on emissions allowances.

The intended emissions cap yields $\bar{A}$ units of abatement by initially distributing a number of allowances equal to $\bar{E} - \bar{A}$, each of which authorizes the holder to emit one unit of CO_2. Combining this emissions cap with the firm's first-order condition yields the resulting level of abatement, allowance price, and cost of abatement:

$$A^0 = \bar{A}$$
$$p^0 = \gamma \bar{A}$$
$$C^0 = \frac{\gamma}{2}\bar{A}^2$$

where the 0 superscript indicates outcomes in autarky. In words, both the allowance price and the abatement cost depend on the emissions cap and the slope of marginal abatement costs.

Linked Emissions Trading

We now consider two independent emissions trading programs, denoted by subscripts i and j, that link through the trade of emissions allowances. All characteristics of the representative firm and policy—such as the abatement cost function and number of allowances issued—can vary across the different programs. Emitters in each program can comply with the emissions policy by holding allowances issued by either program, but allowances are traded between the programs at a mutually agreed exchange rate. We assume each program continues to issue its own unique allowances, rather than jointly issuing a single compliance instrument.[9]

The exchange rate, r, is the number of allowances from program j that are equivalent for compliance purposes to one allowance from program i. In other words, for each unit of CO_2 emitted by the firm in program i, it must have either one allowance from program i or r allowances from program j. Similarly, for each unit of CO_2 emitted by the firm in program j, it must have either one allowance from program j or $\frac{1}{r}$ allowances from program i.

When linking emissions trading programs with an exchange rate, total abatement is not necessarily equal to abatement in autarky because one allowance no longer corresponds to one unit of emissions. Each allowance traded from program i to program j reduces emissions by one unit in program i and increases emissions by r units in program j. That is, at the linked market equilibrium, the following expression must hold:

$$r(A_i - \bar{A}_i) = \bar{A}_j - A_j \tag{2}$$

Additionally, we assume there are no arbitrage opportunities across the programs,[10] so the price of an allowance from program i is r times the price of an allowance from program j:

$$p_i = rp_j \tag{3}$$

Finally, for simplicity, we assume program i has the (weakly) greater autarkic allowance price: $p_i^0 \geq p_j^0$.

Abatement and Abatement Cost

Combining each firm's first-order condition, given in Equation (1), with the linking conditions in Equations (2) and (3), we first solve for the allowance prices in the linked system:

$$p_i = \frac{\bar{A}_i + \frac{1}{r}\bar{A}_j}{\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}} \quad \text{and} \quad p_j = \frac{r\bar{A}_i + \bar{A}_j}{\frac{r^2}{\gamma_i} + \frac{1}{\gamma_j}} \tag{4}$$

Allowance prices in the linked system have an intuitive interpretation: each program's allowance price is the product of total abatement mandated by the two programs and the slope of the

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[9] The same results can be achieved using a single compliance instrument, but the number of allowances issued must be adjusted to account for the exchange rate.

[10] If this were not the case, then any emitter holding the higher-valued allowance could arbitrage the allowance price difference by selling the higher-valued allowance and buying the comparable number of lower-valued allowances.

aggregate marginal abatement cost curve, with all parameters converted to that program's equivalents.[11]

We similarly solve for the level of abatement in each program when linked:

$$A_i = \frac{\bar{A}_i + \frac{1}{r}\bar{A}_j}{\gamma_i\left(\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}\right)} \quad \text{and} \quad A_j = \frac{r\bar{A}_i + \bar{A}_j}{\gamma_j\left(\frac{r^2}{\gamma_i} + \frac{1}{\gamma_j}\right)}$$

We finally solve for the cost to achieve this level of abatement in each of the programs:

$$C_i = \frac{\left(\bar{A}_i + \frac{1}{r}\bar{A}_j\right)^2}{2\gamma_i\left(\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}\right)^2} \quad \text{and} \quad C_j = \frac{\left(r\bar{A}_i + \bar{A}_j\right)^2}{2\gamma_j\left(\frac{r^2}{\gamma_i} + \frac{1}{\gamma_j}\right)^2}$$

These expressions show that the allowance price, level of abatement, and abatement cost in each program depend on the choice of exchange rate—in particular, how the exchange rate compares to the ratio of autarkic allowance prices, $\frac{p_i^0}{p_j^0}$.[12] If the exchange rate is less than this ratio—that is, $r < \frac{p_i^0}{p_j^0}$ —linking decreases allowance price, abatement, and abatement cost in program i and increases these outcomes in program j, as compared to autarky. If the exchange rate is greater than this ratio—that is, $r > \frac{p_i^0}{p_j^0}$ —linking increases allowance price, abatement, and abatement cost in program i and decreases these outcomes in program j, as compared to autarky.

Policymakers in each jurisdiction are likely to be interested in these program-level outcomes, but the overall economic efficiency of an exchange rate depends on the total abatement achieved and the total cost of achieving this abatement. Total abatement and abatement cost in the linked system are given by:

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[11] For example, for program i's allowance price when linked, program j's mandated abatement is converted to program i's allowances by the factor $\frac{1}{r}$ and program j's marginal abatement cost slope is converted to program i's allowances by the factor r^2. The slope of the horizontally summed marginal abatement cost curve is a "harmonic sum," similar to a harmonic mean; the reciprocal of the slope of the aggregated curve is equal to the sum of the reciprocal of each program's slope, which is the denominator in these expressions for allowance prices in the linked system.

[12] As shown in Equation (3), the exchange rate determines the ratio of allowance prices when linked, $r = \frac{p_i}{p_j}$. In this deterministic model, linking at an exchange rate equal to the ratio of autarkic allowance prices, $\frac{p_i^0}{p_j^0}$, yields outcomes that are equivalent to autarky.

$$A_i + A_j = \left(\frac{\bar{A}_i + \frac{1}{r}\bar{A}_j}{\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}} \right) \left(\frac{1}{\gamma_i} + \frac{1}{r\gamma_j} \right)$$

$$C_i + C_j = \frac{\left(\bar{A}_i + \frac{1}{r}\bar{A}_j \right)^2}{2\left(\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j} \right)}$$

These expressions lead to our first result.

Result 1. Linking always (weakly) decreases the total abatement cost, but linking with an exchange rate can increase or decrease the total level of abatement:

i. If $r = 1$ or $r = \frac{p_i^0}{p_j^0}$, total abatement when linked is equal to total abatement in autarky.

ii. If $1 < r < \frac{p_i^0}{p_j^0}$, total abatement when linked is greater than total abatement in autarky.

iii. If $r < 1$ or $r > \frac{p_i^0}{p_j^0}$, total abatement when linked is less than total abatement in autarky.

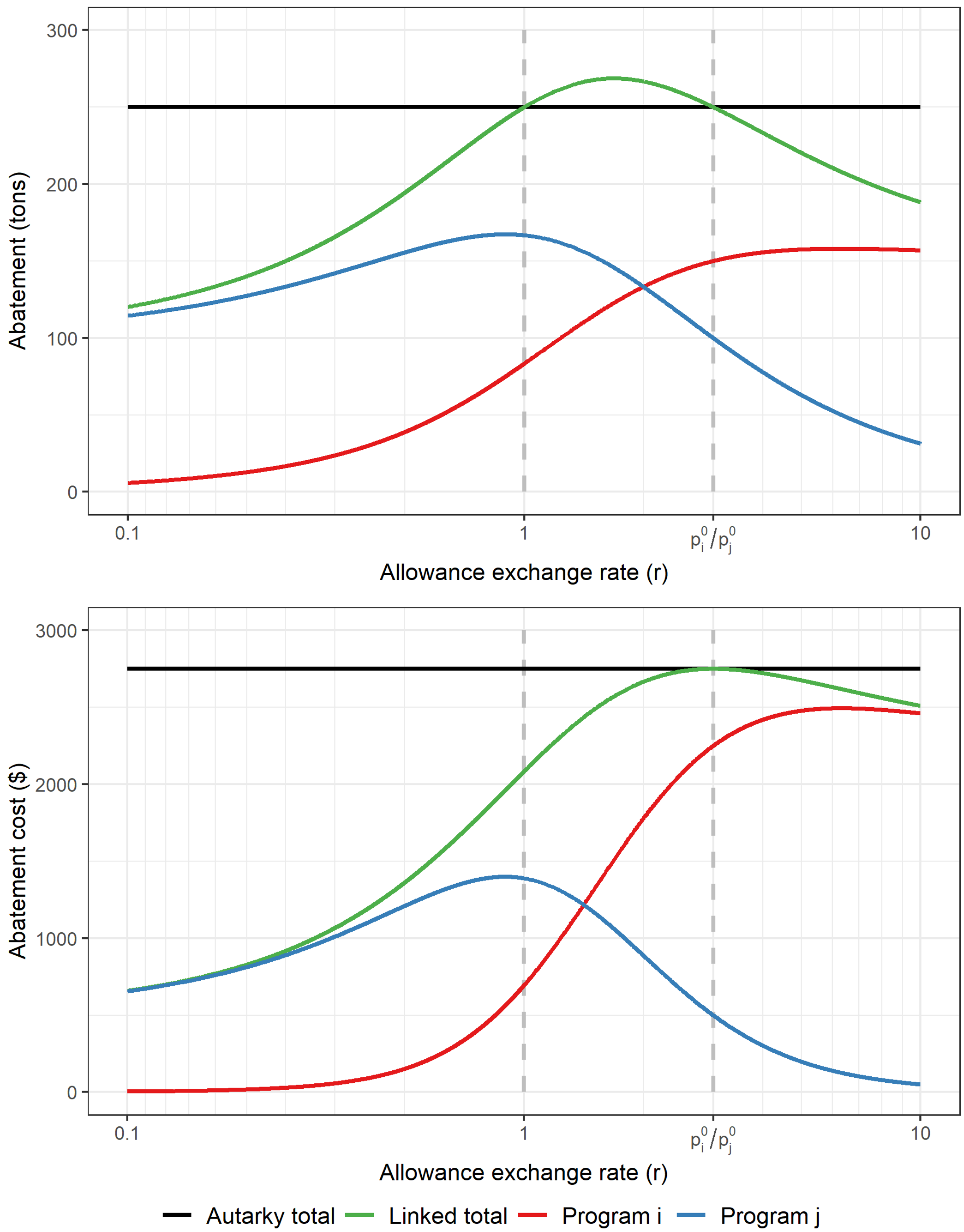
When the exchange rate is less than $\frac{p_i^0}{p_j^0}$, allowances flow from the lower-priced program j to the higher-priced program i. With an exchange rate greater than one, each additional unit of emissions in program i requires more than one allowance from program j, so the overall cap is effectively tightened. This flow of allowances shifts abatement from program i, which has the greater marginal abatement cost, to program j, and this reallocation of abatement reduces the total abatement cost across the linked system. Thus, when the exchange rate is in this core range of $1 < r < \frac{p_i^0}{p_j^0}$, the linked system achieves greater abatement and a lower cost, as compared to autarky.[13]

Conversely, when the exchange rate is outside this core range—that is, $r < 1$ or $r > \frac{p_i^0}{p_j^0}$—the program that imports allowances requires less than one allowance for each unit of emissions, so the overall cap is effectively weakened. This range of exchange rates also reduces the total abatement cost, but only because environmental outcomes are eroded by linking.

[13] Schneider et al. (2017) use a simplified model to describe the effects of linking under varied exchange rates on cost-effectiveness and emissions outcomes. They find a similar range of exchange rates that increase abatement and improve cost-effectiveness, which they describe as "effective" exchange rates. We build on this work by developing this formal model of linking to analyze abatement and abatement cost outcomes.

This result is shown graphically in Figure 1, in which we plot the levels of abatement and the abatement costs for a specific set of parameters;[14] results are qualitatively similar for any set of parameters. In this example, the ratio of autarkic allowance prices is $\frac{p_i^0}{p_j^0} = 3$, which is denoted

Figure 1: Analytical results—Abatement and cost when linked



[14] To generate this figure, we use the following parameters: $\bar{A}_i = 150$, $\gamma_i = 0.2$, $\bar{A}_j = 100$, $\gamma_j = 0.1$.

by a dashed vertical line. At exchange rates in the core range between 1 and $\frac{p_i^0}{p_j^0} = 3$, the linked system achieves greater total abatement at lower cost than in autarky. Total abatement costs are also lower than autarky outside this core range of exchange rates, but only because these more extreme exchange rates effectively loosen the cap and reduce the total level of abatement achieved by the linked system.[15]

This range of exchange rates that yields greater total abatement at lower cost than in autarky—an exchange rate between 1 and $\frac{p_i^0}{p_j^0}$—is also the most likely to be relevant to policymakers. An exchange rate of $\frac{p_i^0}{p_j^0}$, which yields results equal to autarky, represents the status quo if the programs do not link. An exchange rate of 1, which achieves a uniform allowance price across the two programs, represents a traditional link with fully fungible allowances. If policymakers are interested in using an exchange rate to moderate the effects of linking, an outcome between these two benchmark exchange rates is most likely. Thus, linking with an exchange rate is likely to yield environmental and economic benefits, even if these are not the explicit goals of policymakers when negotiating the link.

Optimal Exchange Rate

The fact that total abatement in the linked market depends on the choice of the exchange rate has implications for the socially optimal exchange rate. It is well known that abatement is efficiently allocated when allowance prices are equal across programs and all emitters face the same marginal incentive to abate, which occurs at an exchange rate of $r = 1$. If the total level of abatement is not optimal, however, the theory of the second best suggests it may be socially beneficial to trade off this efficient allocation of abatement in favor of approaching the optimal quantity of abatement.

To determine the socially optimal exchange rate, consider a global pollutant with constant marginal damages d. We assume each program's level of abatement and marginal

[15] Average abatement cost across the linked system—given by the ratio of total abatement cost to total abatement—increases monotonically with the exchange rate as abatement shifts from the lower-cost program j to the higher-cost program i.The total level of abatement also changes with the exchange rate, however, so average abatement cost is not an appropriate metric to compare the economic efficiency of allowance exchange rates.

abatement cost curve are fixed, so the only choice variable is the exchange rate.[16] The social planner seeks to maximize welfare, given by the benefits of abatement net of the costs:

$$\max_{r} d\left(A_i + A_j\right) - \frac{\gamma_i}{2} A_i^2 - \frac{\gamma_j}{2} A_j^2$$

This optimization problem yields the first-order condition:

$$(d - p_i)\frac{\partial A_i}{\partial r} = -\left(d - p_j\right)\frac{\partial A_j}{\partial r}$$

where $d - p_i$ is the net benefit of the marginal unit of abatement in program i and $\frac{\partial A_i}{\partial r}$ is the marginal quantity of abatement in program i with respect to the exchange rate, so the product is the marginal welfare improvement with respect to the exchange rate. Note that both p_i and $\frac{\partial A_i}{\partial r}$ are functions of r. The optimal exchange rate equalizes the magnitude of the marginal welfare improvement in each program.

From this first-order condition, we see that an exchange rate of $r = 1$ is optimal when the linked allowance price—and, hence, the marginal abatement cost in each program—is equal to the marginal damage of emissions, $p_i = p_j = d$.[17] If an exchange rate of 1 yields a linked allowance price that is below d, however, then social welfare can be improved with an exchange rate that increases abatement. Conversely, if an exchange rate of 1 yields a linked allowance price that is above d, then social welfare can be improved with an exchange rate that decreases abatement. Solving for the optimal exchange rate gives our next result.

Result 2. The socially optimal exchange rate is[18]

$$r = \frac{\gamma_i\left(\bar{A}_i\left(2d - p_i^0\right) - \bar{A}_j\left(2d - p_j^0\right)\right) + \gamma_i\sqrt{\left(\bar{A}_i p_i^0 + \bar{A}_j p_j^0\right)\left(\frac{1}{\gamma_i}\left(2d - p_i^0\right)^2 + \frac{1}{\gamma_j}\left(2d - p_j^0\right)^2\right)}}{p_i^0\left(2d - p_j^0\right) + p_j^0\left(2d - p_i^0\right)}$$

This expression yields an optimal exchange rate of $r = 1$ in only two cases. As discussed above, the first case is when setting $r = 1$ results in the linked market price being equal to the

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[16] This situation could arise for many reasons. For example, the legislative branch of government could establish the trading program and mandate the number of emissions allowances, but they may authorize the executive branch to administer the trading program and establish additional program details, such as linking. Additionally, linking of trading programs are likely to be less salient than changes to the number of emissions allowances and, hence, subject to less restrictive political constraints.

[17] Allowance prices when linked are equal if and only if the exchange rate is $r = 1$.

[18] This expression is correct so long as the programs in autarky are not over-abating to an extreme level. If they are, the second term in the numerator is subtracted from the first, rather than added.

marginal damage of emissions, $p_i = p_j = d$. This is the first-best solution, resulting in both the efficient allocation of abatement across the two programs and the efficient level of total abatement. This scenario, however, is unlikely to occur when linking real-world trading programs.[19]

The second case for which $r = 1$ is optimal is when the autarkic allowance prices are equal, $p_i^0 = p_j^0$.[20] This scenario may be more likely than the first to occur, but the linking of trading programs with equal autarkic allowance prices simply yields the same outcomes as autarky. Thus, we conclude that with nearly all real-world trading programs, social welfare is maximized when linking occurs at a rate other than $r = 1$.

If an exchange rate of 1 yields a linked system with too little abatement—that is, the allowance prices when linked are below marginal damages—then the socially optimal exchange rate will always lie within the open interval bounded by 1 and $\frac{p_i^0}{p_j^0}$. As discussed previously, this interval represents exchange rates between uniform trading and autarky, which spans the values most likely to be considered by policymakers, indicating that linking programs using exchange rates theoretically can be expected to achieve outcomes close to the social optimum.

The optimal exchange rate result is shown graphically in Figure 2, in which we plot the climate benefits, abatement cost, and net social welfare gains of the linked system, as compared to autarky, for the same set of parameters used in Figure 1;[21] results are qualitatively similar for any set of parameters yielding too little abatement in autarky. The social welfare gains of linking are maximized when these programs link at an exchange rate of $r \approx 1.5$. Any exchange rate in the range $1 < r < \frac{p_i^0}{p_j^0}$ yields welfare gains compared to autarky, and much of this range yields welfare gains compared to the efficient allocation of abatement from an exchange rate of $r = 1$.

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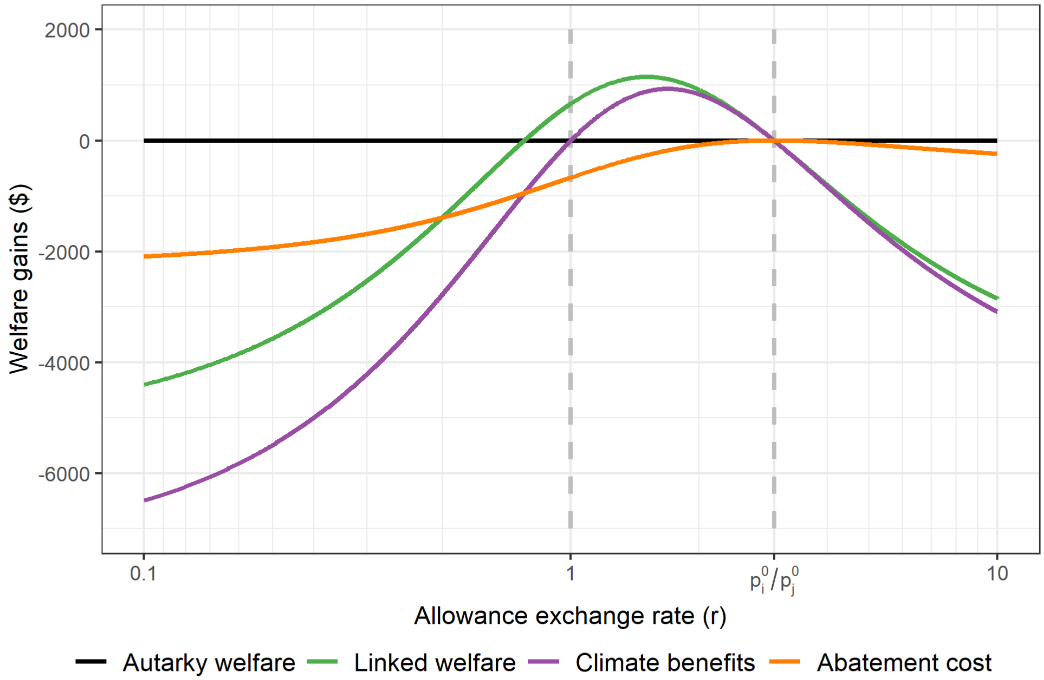
[19] This outcome occurs if and only if emissions caps happen to be set such that $\bar{A}_i + \bar{A}_j = d\left(\frac{1}{\gamma_i} + \frac{1}{\gamma_j}\right)$.

[20] In this case, with $\frac{p_i^0}{p_j^0} = 1$, there is no interval of exchange rates for which linking increases abatement. Thus, if too little abatement occurs in autarky, there is no ability to trade off the efficient allocation of abatement for additional abatement; instead, deviating from $r = 1$ both reduces the efficiency of abatement allocation and moves the linked system further away from the optimal level of abatement. Even in the case of the programs over-abating in autarky, deviating from $r = 1$ reduces social welfare in all but the most extreme cases of over-abatement, because the cost of losing allocative efficiency is greater at higher autarkic prices, so this cost outweighs the benefit of reducing abatement.

[21] To generate this figure, we use the following parameters: $\bar{A}_i = 150$, $\gamma_i = 0.2$, $\bar{A}_j = 100$, $\gamma_j = 0.1$.

Figure 2: Analytical results—Welfare gains compared to autarky when linked



Distributional Effects

Policymakers may be interested not in setting the exchange rate to be socially optimal globally, but rather to benefit their own government or region. To this end, we next show how the choice of the exchange rate differently affects several distributional metrics in each region or sector.

We first consider the revenue raised by the regional government through the sale of allowances.[22] The government revenue (GR) generated by each trading program is the product of the allowance price and the difference between emissions with no carbon emissions policy in place and the intended abatement:

$$GR_i = p_i(\bar{E}_i - \bar{A}_i) \quad \text{and} \quad GR_j = p_j(\bar{E}_j - \bar{A}_j)$$

Under regional linking, these expressions give the revenues raised by each regional government. Under sectoral linking, however, the two sectoral programs are overseen by the same

[22] For this metric, we assume all emissions allowances are sold by the regional government at the market-clearing price; a multi-unit, uniform-price auction is an example of a mechanism that would achieve this outcome. If this is not the case and some allowances are freely allocated, $\bar{E}_i - \bar{A}_i$ and $\bar{E}_j - \bar{A}_j$ should be replaced by the quantity of allowances sold by the respective government.

government, so the expressions describe the two distinct revenue streams for that single government.

We also consider the net flow of allowance revenues into or out of a trading program due to the export or import of emissions allowances. The net revenue flow (NRF) into each trading program is:

$$NRF_i = p_i(A_i - \bar{A}_i) \quad \text{and} \quad NRF_j = p_j(A_j - \bar{A}_j)$$

This metric is more relevant for regional linking and represents revenue flow into or out of the region. Under sectoral linking, which occurs within the same region, there is no interregional exchange of allowances or revenues.

We finally consider total economic surplus—excluding the climate benefits—generated in each trading program, which is a function of net revenue flows less abatement costs. The total economic surplus (TS) in each trading program is:

$$TS_i = p_i\left(\frac{1}{2}A_i - \bar{A}_i\right) + Z_i \quad \text{and} \quad TS_j = p_j\left(\frac{1}{2}A_j - \bar{A}_j\right) + Z_j$$

where Z_i and Z_j represent the remaining economic surplus generated in the output market in each regional sector.[23] Under regional linking, these expressions represent the economic surplus generated for each regional economy. Under sectoral linking, which occurs within the same region, the economic surplus generated in that single regional economy is the sum of these two values.

The distributional metrics in each trading program are functions of that program's allowance price and level of abatement, which depend on the exchange rate. The effect of the exchange rate on each distributional metric is our third result, which we report separately for regional linking (Result 3a) and sectoral linking (Result 3b).

Result 3a. Under regional linking, linking always (weakly) increases the total economic surplus—excluding climate benefits— in each region, but linking with an exchange rate results in opposite revenue effects in each region:

i. If $r < \frac{p_i^0}{p_j^0}$, linking decreases government revenue and net revenue flows in region i but increases government revenue and net revenue flows in region j, as compared to autarky.

[23] As described previously, the level of production and consumption are assumed to be fixed over the time horizon considered. This assumption corresponds well with demand for electricity, which is highly inelastic. Our simulation model also assumes electricity demand and aggregate production are fixed.

ii. If $r > \frac{p_i^0}{p_j^0}$, linking increases government revenue and net revenue flows in region i but decreases government revenue and net revenue flows in region j, as compared to autarky.

Result 3b. Under sectoral linking within the same region, linking always (weakly) increases the total economic surplus—excluding the climate benefits— in the region, but linking with an exchange rate may increase or decrease government revenues.[24]

Consider first an exchange rate that is less than the ratio of autarkic prices: $r < \frac{p_i^0}{p_j^0}$. As shown previously, the firm in program i abates less than in autarky and the firm in program j abates more than in autarky. These levels of abatement yield a flow of allowances from program j to program i and a flow of allowance revenues in the opposite direction. This outflow of revenue from program i, however, is more than offset by the reduction in abatement cost within that program, as compared to autarky; conversely, the inflow of allowance revenue in program j more than offsets the increase in abatement cost within that program, relative to autarky. Thus, due to these gains from trade, total economic surplus generated by each trading program is greater when linked at $r < \frac{p_i^0}{p_j^0}$ than in autarky. If the exchange rate is greater than the ratio of autarkic prices—that is, $r > \frac{p_i^0}{p_j^0}$—allowances and net revenues flow in the opposite directions of those described above, but total economic surplus generated by each trading program continues to increase, as compared to autarky.

Combining this result with the previous results, we conclude that, not only does linking in the core range of exchange rates, $1 < r < \frac{p_i^0}{p_j^0}$, yield greater abatement than autarky at lower cost, but it also yields greater economic surplus—even when excluding the climate benefits— than autarky in each regional economy. Thus, because the exchange rate is expected to fall within this plausible range, linking with an exchange rate is likely to yield environmental benefits globally and economic benefits in each region, even if these are not the explicit goals of policymakers when linking.

Linking in this core range of exchange rates will, however, also affect government revenues and the flow of allowance revenues. For example, under regional linking, an exchange rate in this core range will always yield allowance flows from program j to program i and,

[24] The effect of sectoral linking on government revenue depends not only on how the exchange rate compares to the ratio of autarkic allowances prices, but also on the relative size of the two sectors and the relative stringency of the two trading programs.

hence, revenue flows from region i to region j. Under sectoral linking, an exchange rate in this core range may increase or decrease government revenues, depending on characteristics of the sectors and trading programs. Thus, if a regional government has a different objective function—such as maximizing government revenue or revenue flows into the region to fund investment—then this distributional outcome could instead create a barrier to linking. But linking in this core range of exchange rates will yield distributional outcomes between the bookend cases of no linking and traditional linking with fully fungible allowances, or $r = 1$. As a result, if distributional concerns create a barrier to traditional linking at $r = 1$, an exchange rate in this core range could moderate the distributional effects and engender links that otherwise would not occur.

Price Containment Mechanisms

Many emissions trading programs include a price containment mechanism to constrain the price of an emissions allowance from rising too high or falling too low or both. We add to our model a price collar in each trading program. Each price collar is composed of a price floor, $\bar{p}^F$, and a price ceiling, $\bar{p}^C$.[25] We assume price collars do not bind in either program in autarky, as a binding price collar suggests the policy is constrained by political considerations that could also restrict linking.[26] We further assume that the regional governments do not freely allocate too many emissions allowances such that the price floor becomes irrelevant.[27]

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[25] There are several ways to achieve a price floor and price ceiling in practice. For example, the regional government could auction allowances with a reserve price of $\bar{p}^F$ and further offer an unlimited number of additional allowances for sale at a price of $\bar{p}^C$.

[26] There are several reasons why the design of the emissions trading program might yield prices at the price floor or price ceiling, which we abstract away from in this analytical framework. Policymakers may not know *ex ante* what the abatement cost will be, and this uncertainty may result in allowance prices at the floor or ceiling. Other companion policies could reduce the demand for allowances within the state and tend to suppress prices. Additionally, policymakers may face many political constraints when designing a trading program, and in trying to balance competing demands, an allowance price at the floor or ceiling may be the only politically feasible outcome.

[27] In many emissions trading programs, some allowances are freely allocated to emitters or other agents for political or economic reasons, such as building political support for the trading program or to compensate firms for their cost of compliance, which can have important implications for firm entry and exit and emissions leakage. In this analytical model, however, freely allocated allowances will affect market outcomes only if the market is sufficiently oversupplied through free allocation and no allowances are sold by the government through an auction or other mechanism, which will yield an allowance price below the reserve price. This example is an extreme case that has not been observed in any allowance markets to date, although bilateral (spot) market prices have been observed to fall below auction reserve prices during periods between auctions. Programs that have free allocation may require the consignment of those allowances to an auction with proceeds returned to the original allowance holder, as in the sulfur dioxide trading program, and for allowances freely allocated to electricity and natural gas utilities in California's CO_2 trading program (Burtraw and McCormack 2017).

When the two trading programs link, the effective price collar in each program is the tightest combination of price floor and price ceiling after converting prices at the exchange rate. That is, when linked at exchange rate r, the effective price collar in program i has a price floor that is the greater of $\bar{p}_i^F$ and $r\bar{p}_j^F$ and a price ceiling that is the lesser of $\bar{p}_i^C$ and $r\bar{p}_j^C$. Similarly, the effective price collar in program j has a price floor that is the greater of $\frac{1}{r}\bar{p}_i^F$ and $\bar{p}_j^F$ and a price ceiling that is the lesser of $\frac{1}{r}\bar{p}_i^C$ and $\bar{p}_j^C$. Thus, the price collar each program faces in a linked market will always be weakly tighter than its price collar in autarky. Additionally, the exchange rate will determine each program's effective price collar, with more extreme exchange rates yielding tighter price collars.

An additional consideration is that each program's effective price collar must have a ceiling that is weakly greater than the floor. This practical constraint restricts the feasible set of exchange rates to the range $\frac{\bar{p}_i^F}{\bar{p}_j^C} \leq r \leq \frac{\bar{p}_i^C}{\bar{p}_j^F}$. For example, if there is no overlap in the nominal price collars—that is, $\bar{p}_i^F > \bar{p}_j^C$—then the programs could not feasibly link at the traditional exchange rate of $r = 1$. At the extremes of $r = \frac{\bar{p}_i^F}{\bar{p}_j^C}$ or $r = \frac{\bar{p}_i^C}{\bar{p}_j^F}$, the effective price collar in each program is tightened to the maximum extent possible and the linked trading system becomes equivalent to a carbon tax.

Using the expressions for allowance prices in the linked system given in Equation (4), we finally show how the choice of exchange rate determines if the linked system is at a price floor, price ceiling, or within the price collar. We begin by considering a linked system in which program i's price floor is binding. This only occurs if the allowance price in program i when linked would otherwise have been below the price floor:

$$p_i = \frac{\bar{A}_i + \frac{1}{r}\bar{A}_j}{\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}} \leq \bar{p}_i^F$$

We then solve for the values of r that yield this inequality. We similarly solve for the exchange rates that yield the other price collar outcomes, which gives our final result.

Result 4. The exchange rate, r, determines the linked system outcome:

i. If $r \leq \frac{-\frac{\gamma_i}{\gamma_j}p_j^0 + \sqrt{\left(\frac{\gamma_i}{\gamma_j}p_j^0\right)^2 + 4\frac{\gamma_i}{\gamma_j}\bar{p}_i^F(p_i^0 - \bar{p}_i^F)}}{2(p_i^0 - \bar{p}_i^F)}$, then the price floor of program i binds with $p_i = \bar{p}_i^F$ and $p_j = \frac{1}{r}\bar{p}_i^F$.

ii. If $\frac{p_i^0 - \sqrt{(p_i^0)^2 - 4\frac{\gamma_i}{\gamma_j}\bar{p}_j^C(\bar{p}_j^C - p_j^0)}}{2\bar{p}_j^C} \leq r \leq \frac{p_i^0 + \sqrt{(p_i^0)^2 - 4\frac{\gamma_i}{\gamma_j}\bar{p}_j^C(\bar{p}_j^C - p_j^0)}}{2\bar{p}_j^C} \leq$, then the price ceiling of program j binds with $p_i = r\bar{p}_j^C$ and $p_j = \bar{p}_j^C$.

iii. If $\frac{\frac{\gamma_i}{\gamma_j}p_j^0 - \sqrt{\left(\frac{\gamma_i}{\gamma_j}p_j^0\right)^2 - 4\frac{\gamma_i}{\gamma_j}\bar{p}_i^C(\bar{p}_i^C - p_i^0)}}{2(\bar{p}_i^C - p_i^0)} \leq r \leq \frac{\frac{\gamma_i}{\gamma_j}p_j^0 + \sqrt{\left(\frac{\gamma_i}{\gamma_j}p_j^0\right)^2 - 4\frac{\gamma_i}{\gamma_j}\bar{p}_i^C(\bar{p}_i^C - p_i^0)}}{2(\bar{p}_i^C - p_i^0)}$, then the price ceiling of program i binds with $p_i = \bar{p}_i^C$ and $p_j = \frac{1}{r}\bar{p}_i^C$.

iv. If $r \geq \frac{p_i^0 + \sqrt{(p_i^0)^2 + 4\frac{\gamma_i}{\gamma_j}\bar{p}_j^F(p_j^0 - \bar{p}_j^F)}}{2\bar{p}_j^F}$, then the price floor of program j binds with $p_i = r\bar{p}_j^F$ and $p_j = \bar{p}_j^F$.

v. Otherwise, the linked system clears inside the price collar with the allowance prices given in Equation (4).

In words, if the exchange rate is sufficiently low, then the system clears at the price floor of program i.[28] Relative to autarky, this exchange rate yields a lower allowance price and less abatement in program i, but a higher allowance price and more abatement in program j. Thus, the effect on total abatement of linking within this interval of exchange rates is ambiguous. Conversely, if the exchange rate is set sufficiently high, then the system clears at the price floor of program j and the effects of linking are the reverse of the effects at program i's price floor.

There are also intervals of exchange rates that, in theory, result in the system clearing at a price ceiling, as defined above. The nature of the linked system, however, moderates high allowance prices and imposes an implicit price ceiling.[29] In Figure 3 we plot allowance prices—excluding a price collar—for the same set of parameters used in Figures 1 and 2;[30] results are

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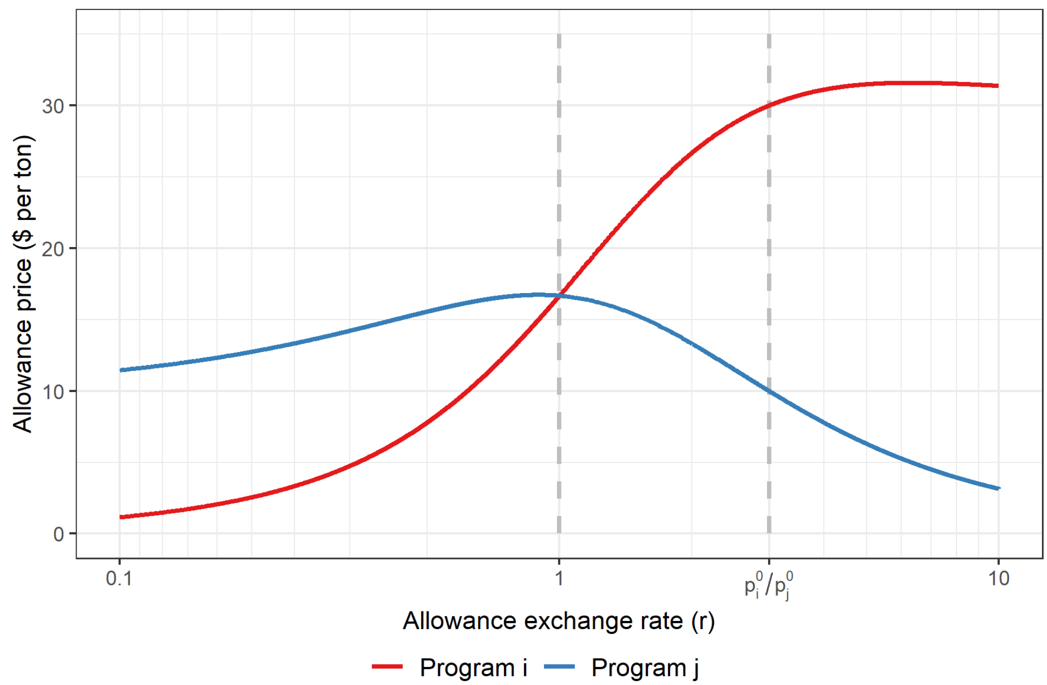
[28] It is possible, depending on the parameters of each program, for this or any of the exchange rate intervals in Result 4 to fall outside the feasible set of exchange rates—that is, $\frac{\bar{p}_i^F}{\bar{p}_j^C} \leq r \leq \frac{\bar{p}_i^C}{\bar{p}_j^F}$—and, thus, not be a feasible outcome for the linked market. It is additionally possible, in theory, for overlap to occur between the intervals in (i) and (ii) or the intervals in (iii) and (iv). This overlap only occurs outside the feasible set of exchange rates, however, so each exchange rate within the feasible set yields only one of the outcomes given in Result 4.

[29] Linking at an exchange rate of $r = 1$ moderates both high and low allowance prices by equating allowance prices in the linked system at a price between the autarkic prices. Using a different exchange rate, however, introduces a wedge between these prices, which tends to drive prices down. The program with the lower price imports allowances from the higher-priced program, but each allowance corresponds to more emissions in the lower-priced program in most cases, so total abatement decreases across the linked system. This lower level of abatement corresponds to lower allowance prices.

[30] To generate this figure, we use the following parameters: $\bar{A}_i = 150$, $\gamma_i = 0.2$, $\bar{A}_j = 100$, $\gamma_j = 0.1$.

qualitatively similar for any set of parameters. Each program has a maximum allowance price that can result from the linked system, regardless of either program's price ceiling.[31] If this maximum price is below the program's price ceiling, then the price ceiling is superfluous and will never bind. In this case, the exchange rate intervals corresponding to price ceilings do not exist. Because linking has this effect of moderating high allowance prices, price floors are likely to play a greater role in constraining linked markets than are price ceilings.

Figure 3: Analytical results—Allowance prices when linked



In summary, the role of price containment mechanisms can be potentially complicated when linking trading programs with an exchange rate. In some cases, such as when nominal price collars do not overlap, an exchange rate may allow for links that otherwise would be infeasible. In other cases, however, the presence of price collars may constrain the feasible range of exchange rates to be considered and the possible linked market outcomes.

[31] The maximum allowance price in program i when linked is $p_i^{MAX} = \frac{1}{2}\left(p_i^0 + \sqrt{(p_i^0)^2 + \frac{\gamma_i}{\gamma_j}\left(p_j^0\right)^2}\right)$, so program i's price ceiling will never bind in a linked market when $\bar{p}_i^C > p_i^{MAX}$. Additionally, when this inequality holds, the interval of exchange rates in (iii) above is not defined by real numbers. Program j has a maximum price of $p_j^{MAX} = \frac{1}{2}\left(p_j^0 + \sqrt{\left(p_j^0\right)^2 + \frac{\gamma_j}{\gamma_i}(p_i^0)^2}\right)$, resulting in similar restrictions.

3. Simulation Model of Linking

In the previous section, we used a simple analytical model to demonstrate how the linked allowance exchange rate can affect abatement, welfare, and distributional outcomes. To do so, however, we abstracted from some of the complexities of real-world policies and markets. In this section, we turn to the Haiku electricity sector simulation model—which incorporates many of these additional characteristics—to provide an in-depth analysis of a link between two hypothetical emissions trading programs. We use the simulation model to confirm the main results and to investigate additional outcomes that are beyond the scope of the analytical model.

Model Description

Haiku is a linear programming model of the United States electricity sector that minimizes costs in the 48 contiguous states across a 30-year time horizon with annual operations determined by 24 representative hours. The model represents generators in each state as model plants characterized by fuel and technology, including options for new investment in both fossil-fired generators and renewables technologies. The linear program uses a constrained optimization approach to represent capacity investment, emissions regulations, performance standards, and other important characteristics of the electricity sector. Output from the model is determined with perfect foresight allowing policies in the future to affect capacity decisions in earlier years. The Haiku model has been used on many occasions to inform the policy-making process.[32]

To align the simulation model structure more closely with the analytical model framework, we make some adjustments to Haiku's standard assumptions.[33] Because of these adjustments, as well as our implementation of a single-year emissions cap for hypothetical trading programs that we describe below, these simulation results do not provide expected outcomes for any real-world policy and should not be used to advise specific policy decisions. Instead, this simulation modeling indicates that the results of our simple analytical model generally persist in this more complex framework that uses empirical data on an emissions-intensive industry, and it identifies additional outcomes that will be important for policymakers to evaluate and consider in real-world policy decisions.

[32] See Shobe, Artuso, and Domeshek (2021) and Burtraw et al. (2019) for recent examples.

[33] First, to negate for the possibility of emissions leakage, we shut down transmission to states outside of each linked region. Second, we disable battery storage units for similar reasons. Third, to focus on contemporaneous rather than dynamic effects, we fix capacity and generation to a baseline scenario except in the year that the emissions trading scheme is in existence.

Model Scenarios

The policy case we construct is a scenario of two regional emissions caps that exist for a single year, 2025.[34] The first regional cap encompasses all states in the Western Interconnection, and we model an emissions cap that reduces CO_2 emissions by 95 million tons from baseline in this region. The second regional cap includes the states in the Eastern United States that are members of the Regional Greenhouse Gas Initiative or the PJM market, and we model an emissions cap that reduces CO_2 emissions by 85 million tons from baseline in this region. We simulate electricity markets outcomes with these regional trading programs in autarky, and we then simulate outcomes when these programs link at various allowance exchange rates. To achieve these emissions reductions in autarky, the allowance price in the West is 3.24 times that in the East, so we consider allowance exchange rates that range from 0.8 to 4, spanning beyond the core range that would likely be considered by policymakers.[35] We also simulate two additional scenarios that include price containment mechanisms, which we describe later.

Abatement and Abatement Cost

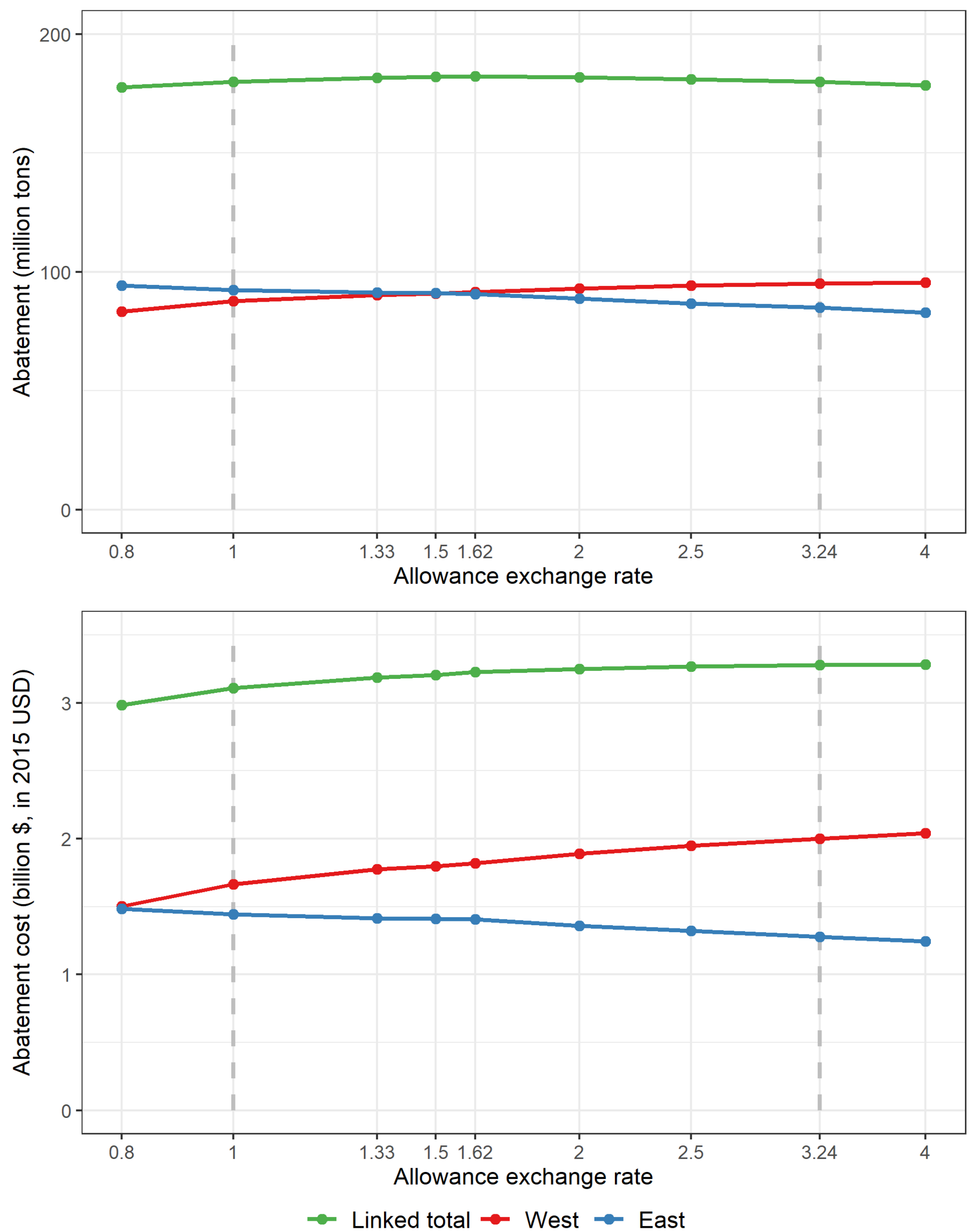
Figure 4 plots the levels of abatement and the abatement costs in each program and for the linked system in total under each of the simulated allowance exchange rates. These results are qualitatively similar to the results of the analytical model: at exchange rates in the core range between 1 and the autarky price ratio of 3.24, the linked system achieves greater total abatement at lower cost than in autarky. As we decrease the exchange rate from 3.24 down to 1, more abatement is achieved in the lower-cost East region and less in the higher-cost West, reducing the aggregate cost of abatement. This shift in abatement is achieved because emitters in the West import allowances from the East, and in this range of exchange rates, more than one allowance must be imported for every ton emitted, so this flow of allowances also reduces emissions. We find that total abatement is maximized at an exchange rate of 1.62, with a modest increase in abatement as compared to either autarky or linking at an exchange rate of 1.

We further summarize these results in Figure 5, which plots the relationship between abatement and average abatement cost; the number next to each point indicates the allowance exchange rate that achieves that outcome. We see that lowering the allowance exchange rate from 4 down to 1.62 increases total abatement in the system and reduces the average abatement

[34] A single-year emissions cap allows us to focus on the contemporaneous effects of the policies in that single year, rather than their longer-run dynamics over many years.

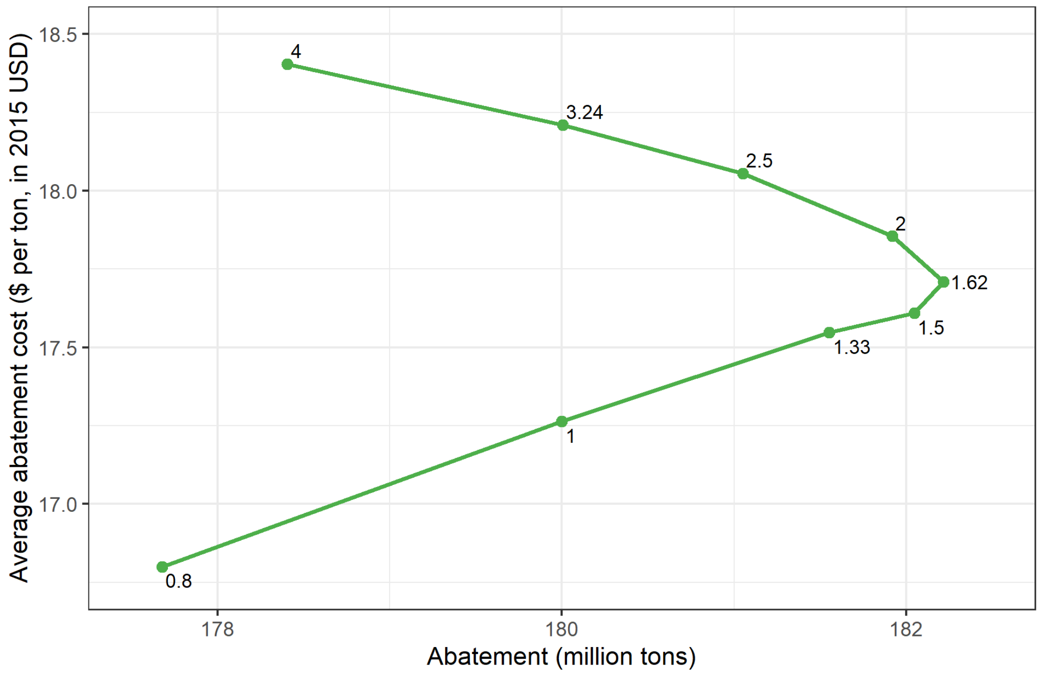
[35] We simulate links at allowance exchange rates of 0.8, 1, 1.33, 1.5, 1.62, 2, 2.5, 3.24, and 4.

Figure 4: Simulation results—Abatement and cost when linked



cost, generating both economic gains and climate benefits. Further lowering the allowance exchange rate below 1.62 continues to reduce the average abatement cost, but it also reduces total abatement, creating a tradeoff between lower costs and improved environmental ambition.

Figure 5: Simulation results—Average abatement cost when linked



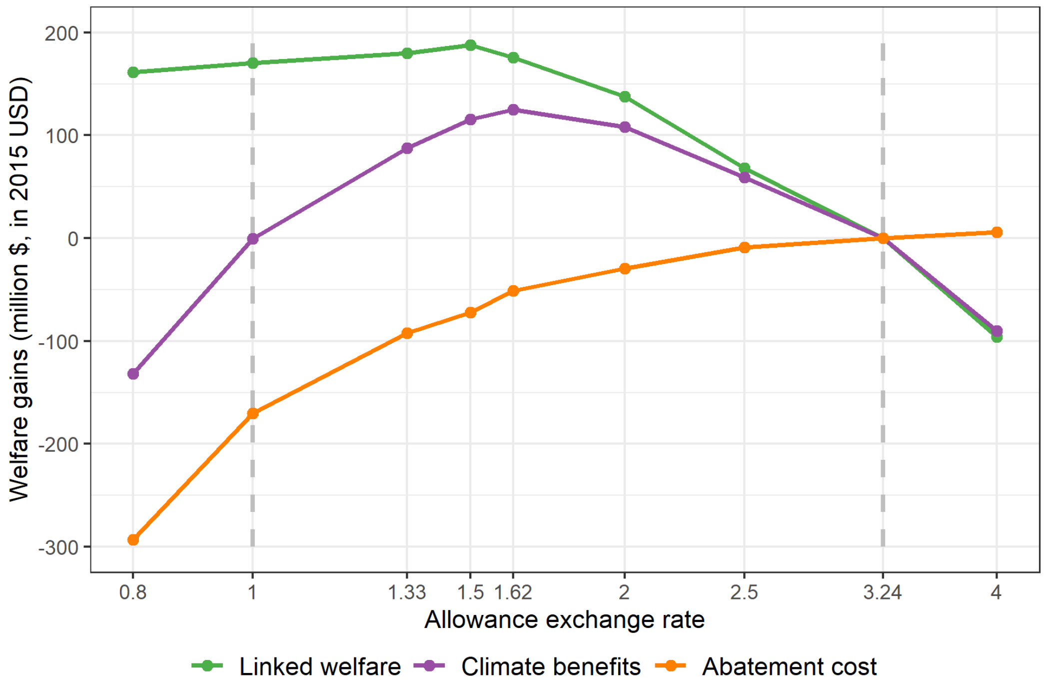
Social Welfare

We also see this tradeoff between abatement costs and climate benefits in Figure 6, in which we plot the welfare gains from linking compared to autarky. We again see that abatement costs monotonically decrease as the allowance exchange rate declines, but climate benefits are a nonmonotonic function of the exchange rate.[36] As a result, social welfare is maximized when these regional trading programs link at an allowance exchange rate of 1.5. Importantly—and in line with the results of our analytical model—social welfare is not maximized at an exchange rate of 1, which equates marginal abatement costs across the two programs. Instead, even though an exchange rate of 1.5 yields a less efficient allocation of abatement across the two programs, it achieves greater abatement and climate benefits that more than offset the abatement costs. The overall difference is modest, however, and any exchange rate between 1 and 1.62 yields welfare gains that may be considered roughly comparable by policymakers.[37]

[36] We value CO_2 abatement at the social cost of carbon estimated by the Interagency Working Group on the Social Cost of Greenhouse Gases (2021). We use the average social cost of carbon emitted in 2025 assuming a 3% discount rate, which they estimate as $56 per metric ton in 2020 USD. We convert this value to $56.51 per short ton in 2015 USD.

[37] If we assume a higher social cost of carbon, such as $83 per ton from using a 2.5% discount rate, then this comparison becomes more favorable for allowance exchange rates that yield greater levels of total abatement. In that case, an exchange rate of 1.5 is more clearly the socially optimal choice.

Figure 6: Simulation results—Welfare gains compared to autarky when linked

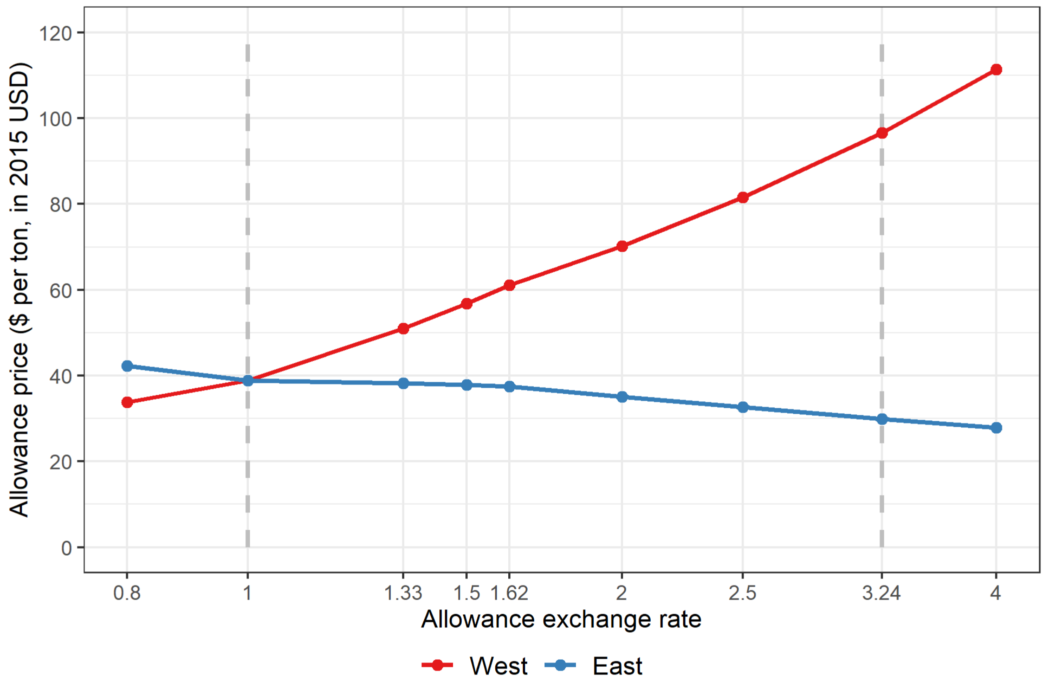


Distributional Effects

The climate benefits of linking accrue globally, rather than within the regions where the abatement occurs, so the local economic consequences of linking come from changes in abatement costs and flows of allowance values. These economic benefits or costs of linking may not be distributed evenly across the two trading programs or among different participants within each program. For example, higher allowance prices increase government revenues from allowances sales but also increase compliance costs for emitters. Figure 7 shows how the choice of allowance exchange rate affects the allowance price, or marginal cost of abatement, in each trading program. We see that lowering the exchange rate greatly reduces the allowance price in the West and yields a relatively small price increase in the East.

Figure 8 plots how these allowance prices translate into changes in revenue for the governments that issue the allowances and changes in compliance costs for emitters covered by each trading program. Lowering the allowance exchange rate, which decreases the allowance price in the West, greatly reduces both the revenue collected by the government and the compliance cost incurred by emitters in the West; at an exchange rate of 1, these values fall by more than $6 billion compared to autarky. Conversely, linking at an allowance exchange rate of 1 increases both government revenue and compliance cost in the East by roughly $3 billion compared to autarky. In fact, at any exchange rate below the autarky price ratio of 3.24, emitters

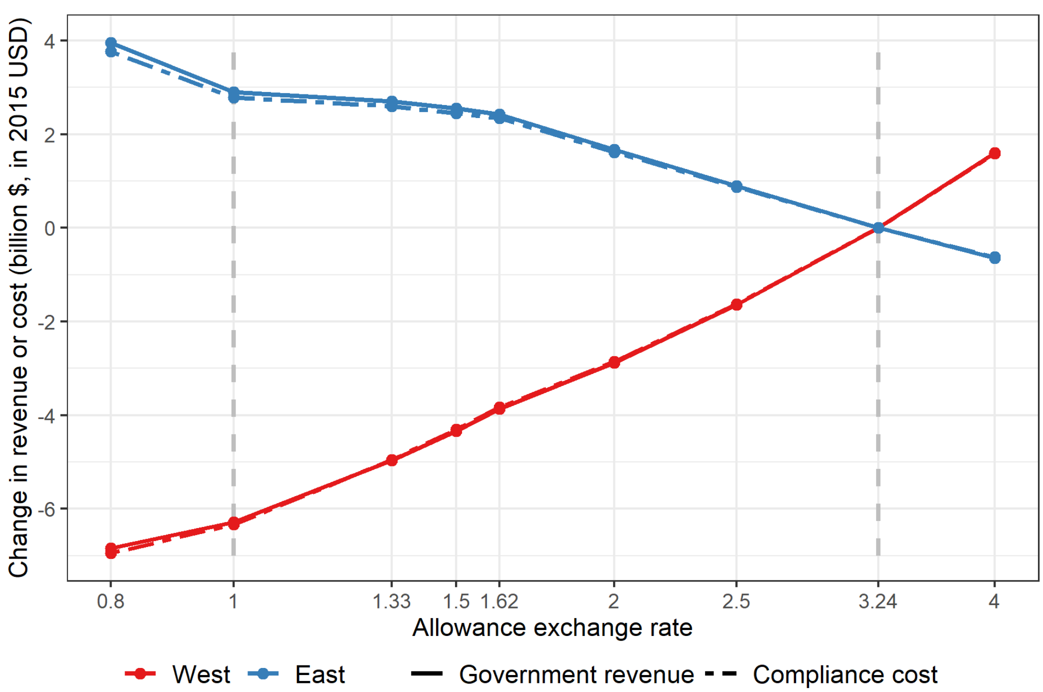
Figure 7: Simulation results—Allowance prices when linked



in the West and governments in the East experience benefits, while governments in the West and emitters in the East experience large losses.

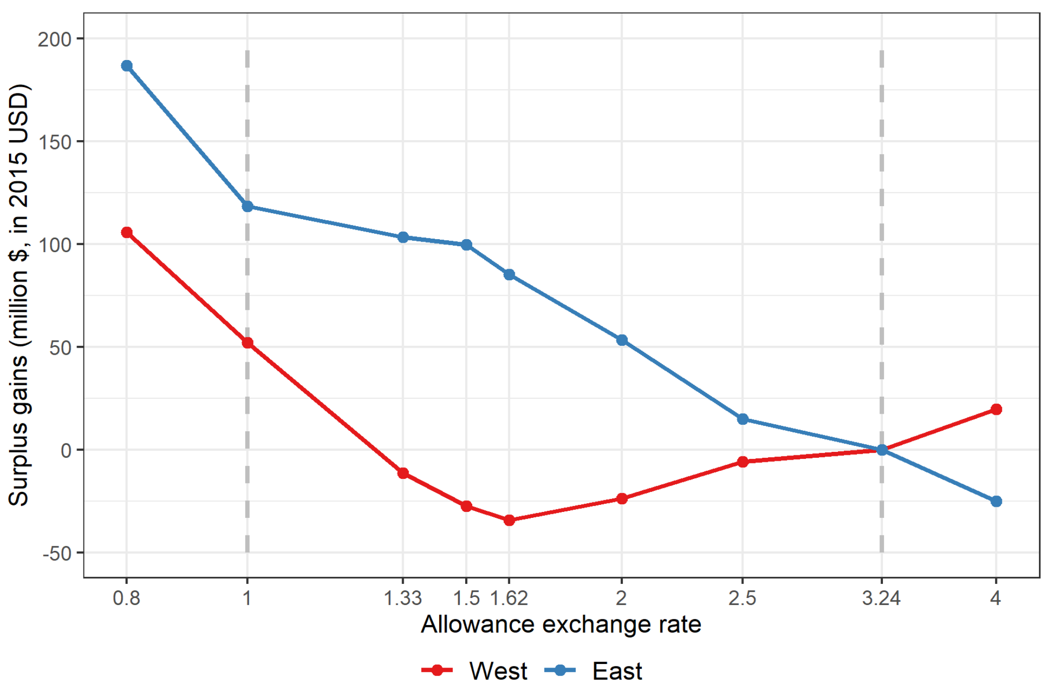
These large distributional effects of linking—particularly the losses for governments in the West and emitters in the East—may create opposition to the link among important

Figure 8: Simulation results—Change in revenue and cost compared to autarky when linked



stakeholders. Using an allowance exchange rate other than the traditional rate of 1 can moderate these distributional effects and may reduce opposition to linking; for example, at an exchange rate of 2, these distributional effects are only half to two-thirds of what they are at a rate of 1. Additionally, within-region transfers could be used to offset revenue reductions or compliance cost increases. In that case, a more relevant metric to evaluate linking would be the total economic surplus gain or loss in each region from linking, which is the difference between changes in government revenue and compliance cost, and which we plot in Figure 9. Although our analytical result states that both regions should gain economic surplus from linking at any exchange rate, here we see that the West loses surplus for many of the exchange rates in the core range, which could impede the linking of these trading programs. These surplus losses occur because—as shown by the allowance prices and abatement levels that result from simulation modeling—the marginal abatement costs in the West are convex over this range of exchange rates, rather than linear as in our analytical model, which yields less cost reductions from linking. Thus, we find that the use of an exchange rate can moderate the distributional effects of linking, but it may not be sufficient to overcome all political economy constraints in all cases.

Figure 9: Simulation results—Regional surplus gains compared to autarky when linked

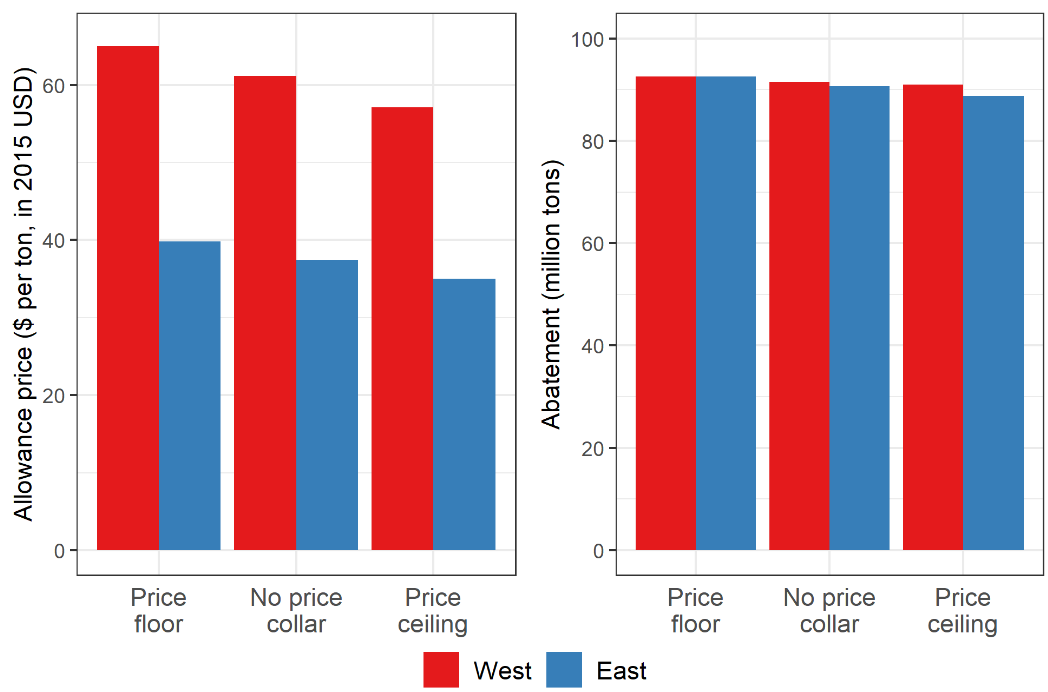


Price Containment Mechanisms

Another aspect of the political economy of negotiating a linking regime is the integrity of the price control mechanism in each program and the ability of one program's price collar to affect allowance prices and abatement in both programs. To explore this issue, we consider two price control mechanisms: a price floor of $65 per ton in the higher-priced West and a price ceiling of $35 per ton in the lower-priced East. We simulate a link at an allowance exchange rate of 1.62—the rate that maximizes linked abatement in the absence of price containment mechanisms—with either the price floor or the price ceiling in effect. With neither price containment mechanism in place, a rate of 1.62 yields allowance prices of $61.15 per ton in the West and $37.44 per ton in the East. Thus, with both price containment mechanisms in place, it would be impossible for the programs to link at an exchange rate of 1.62, or any rate below 1.86,[38] because it would be infeasible to satisfy the price floor and the price ceiling simultaneously.

Figure 10 plots the resulting allowance prices and abatement when these programs link at an allowance exchange rate of 1.62 with the West's $65 per ton price floor, no price containment mechanism, and the East's $35 per ton price ceiling, respectively. As expected, we find that the

Figure 10: Simulation results—Outcomes when linked with a price containment mechanism



[38] The ratio of the West's $65 per ton price floor to the East's $35 per ton price ceiling is 1.86. At an allowance exchange rate of 1.86, both price containment mechanisms would bind simultaneously and the linked system would effectively have regionally differentiated carbon taxes of $65 per ton in the West and $35 per ton in the East. At any rate below 1.86, including a traditional link at a rate of 1, the effective price floor in the West would exceed the effective price ceiling in the East, so it would be impossible to maintain a functioning market at these exchange rates.

price floor in the West bolsters allowance prices in both programs, yielding greater abatement than with no price containment mechanism; although not shown, these higher allowance prices also imply greater government revenue and greater compliance costs in each program. Conversely, the price ceiling in the East suppresses allowance prices in both programs and yields less abatement, lower government revenues, and lower compliance costs in both programs. If some of these outcomes are not in line with stakeholder preferences, then the presence of price containment mechanisms may further complicate the political economy of linking trading programs.

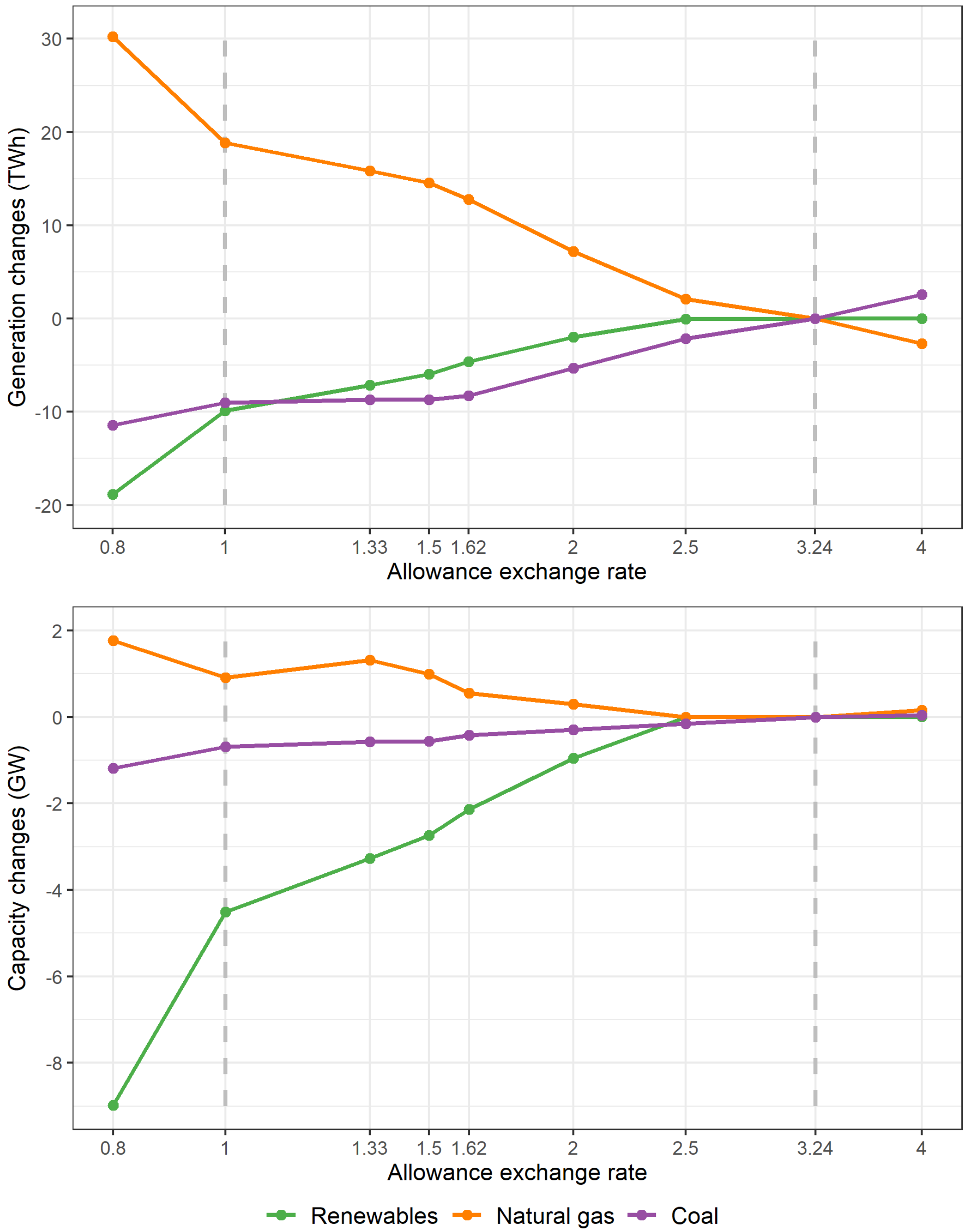
Generation and Capacity Mix

The Haiku electricity sector simulation model includes a detailed representation of both annual operations and capacity investments, so we can investigate how abatement is achieved in autarky and when the trading programs link. Figure 11 shows how the allowance exchange rate affects the generation and capacity mix across the linked system. In the higher-marginal-cost West, abatement is achieved by substituting to renewables; in the lower-marginal-cost East abatement is achieved by fuel switching between coal-fired and natural gas-fired units. Thus, lowering the allowance exchange rate, which shifts abatement from the West to the East, yields less generation from both renewables and coal units with a corresponding increase in generation from natural gas units. The reduction in generation from renewables occurs because less renewables capacity is built in the West at lower exchange rates, whereas fuel switching between fossil fuels results in only small changes in coal and natural gas capacity.

Other Air Pollutants

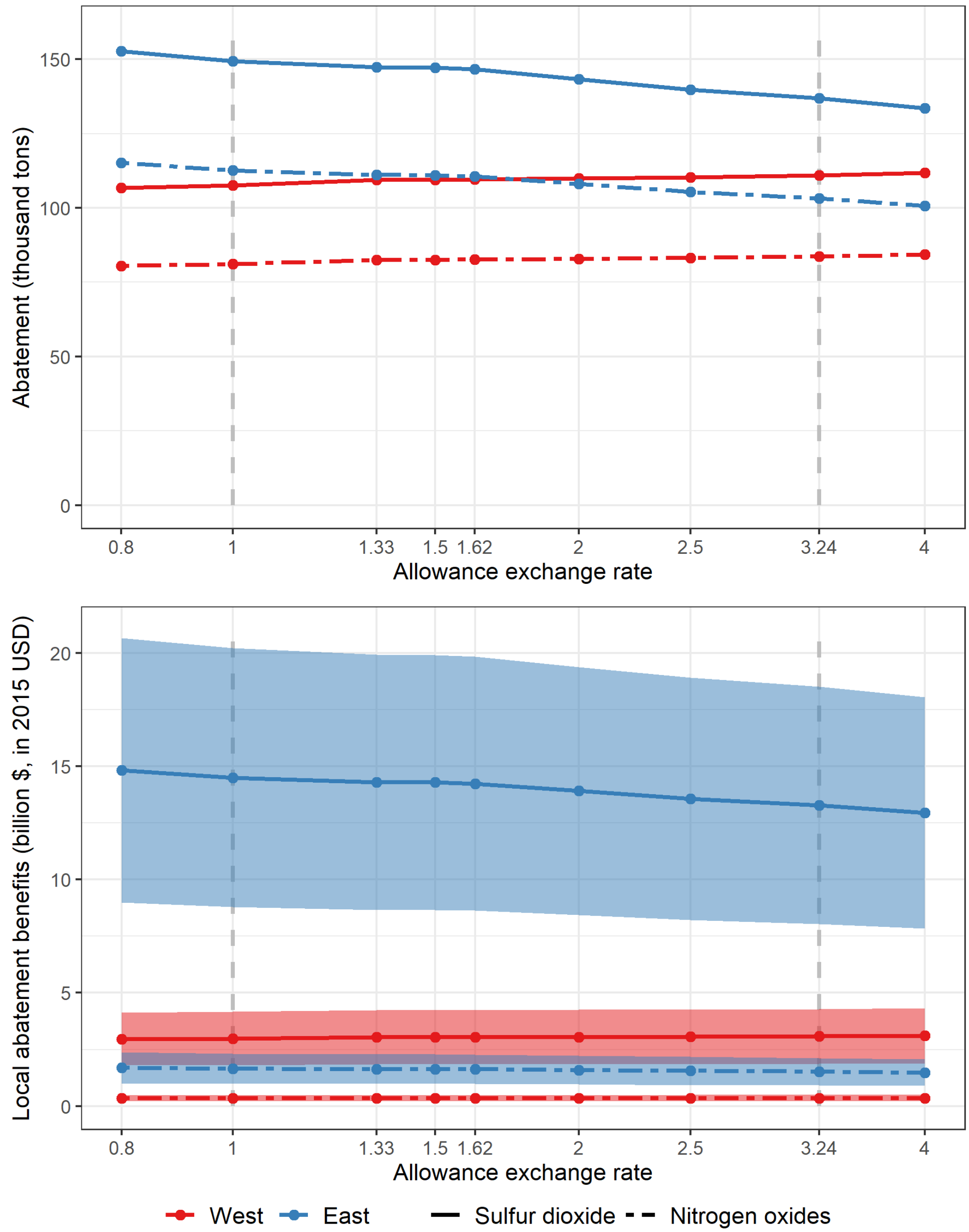
These shifts in generation sources when linked, compared to autarky, yield changes in emissions of not only CO_2 but also other air pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x). The top panel of Figure 12 plots how abatement of SO_2 and NO_x vary with the allowance exchange rate. Lowering the exchange rate increases abatement of both SO_2 and NO_x in the East through fuel switching from coal to natural gas, and it slightly reduces abatement of both pollutants in the West due to lower renewables penetration. Reducing emissions of SO_2 and NO_x yields health benefits within the region where the pollutants are emitted. These benefits are regionally heterogenous and are estimated by the U.S. Environmental Protection Agency (2011) to be 3.5 times greater in the East than in the West. Additionally, there is uncertainty about the health benefits of abating SO2 and NOx, so we calculate a range of benefits in each trading program.[39]

Figure 11: Simulation results—Generation and capacity when linked



[39] We use estimates from Krewski et al. (2009) as a lower bound and estimates from Lepeule et al. (2012) as an upper bound for the health benefits of abating SO_2 and NO_x. Our calculations of health benefits are relative simple and could be improved upon with a higher resolution simulation of local air pollutants and health benefits due to fuel switching. Additional details on the incidence of these health benefits could also help further refine the calculation.

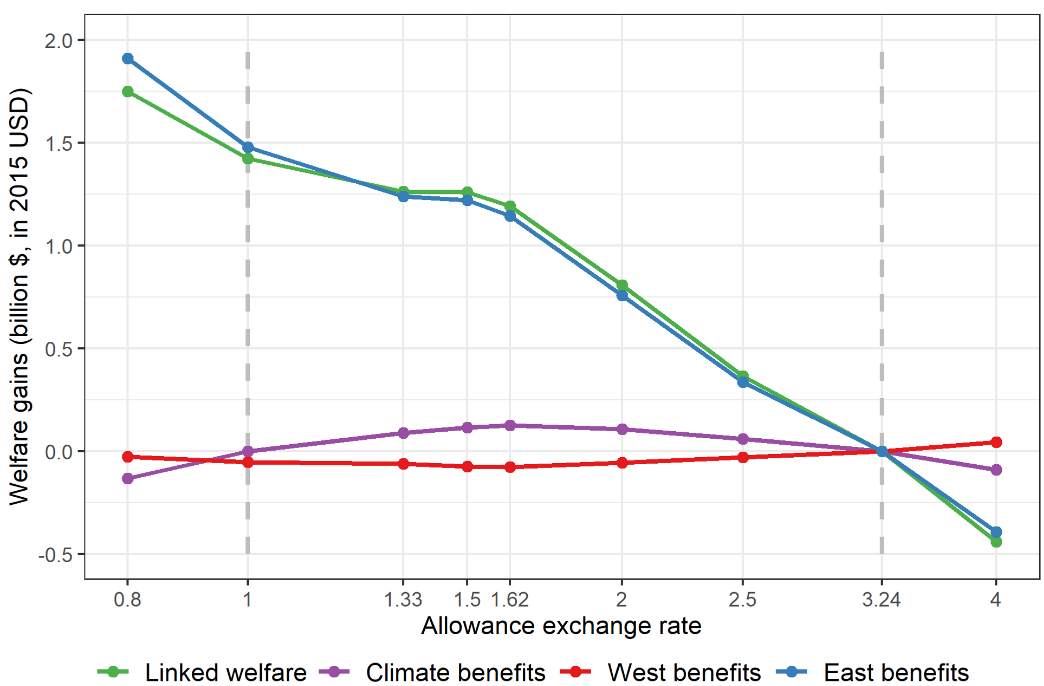
Figure 12: Simulation results—Abatement and abatement benefits of other air pollutants when linked



The bottom panel of Figure 12 plots the local health benefits from abatement of SO_2 and NO_x; the shaded areas give the full range of health benefits, and each point gives the midpoint of the range. We see that SO_2 reductions in the East generate \$8 billion to \$18 billion of health benefits at the autarky price ratio of 3.24, and lowering the allowance exchange rate further increases these benefits. The West also experiences health benefits from abatement, but they are smaller and tend to decrease as the allowance exchange rate declines.

To fully account for the welfare effects of linking these trading programs with an exchange rate, we must also account for these local health benefits from SO_2 and NO_x abatement. Figure 13 plots the welfare gains across the linked system, including the health benefits from SO_2 and NO_x abatement, due to linking with an allowance exchange rate; the figure also indicates the gains that accrue globally to the climate and locally in in each trading program.[40] The vast majority of welfare gains from linking at an allowance exchange rate in the core range, or even below 1, is due to the health benefits in the East from reducing SO_2 and NO_x emissions. Additionally, the welfare loss in the West is minor by comparison. Thus, depending on the priorities of the governments in each region, the consideration of co-benefits could dramatically alter the political economy of negotiating an allowance exchange rate. In fact, from a social welfare perspective, these results indicate that an exchange rate of 0.8, which maximizes reductions of SO_2 emissions in the East—or an even lower allowance exchange rate—would be the optimal policy choice.

Figure 13: Simulation results—Welfare gains including health benefits compared to autarky when linked



[40] In calculating the welfare gains from link in Figure 13, we use the midpoint of the health benefits depicted in Figure 12.

Summary

In summary, our simulation modeling replicates several of the main results from our analytical model. In particular, linking at an allowance exchange rate in the core range—that is, between 1 and the autarky price ratio—achieves greater CO_2 abatement than either bookend exchange rate, and it does so at lower abatement cost than autarky. As a result, the socially optimally exchange rate is not a rate of 1, which equates marginal costs across the two programs, but rather an exchange rate in this core range that yields greater CO_2 abatement and climate benefits. In contrast to the analytical model, however, we find that linking in this core range causes one region to lose economic surplus, which may pose political economy challenges for a potential link.

This simulation modeling also explores several aspects of linking that are beyond the scope of our analytical model and reveals outcomes that deserve careful evaluations when policymakers consider a real-world link. In particular, we find that the choice of allowance exchange rate can greatly affect the generation mix and other air pollutant emissions in each program. In some settings, these co-benefits from SO_2 and NO_x abatement could be large enough to drive the decision to link CO_2 trading programs.

As we described previously, our simulations of single-year emissions caps for hypothetical trading programs should not be used to inform any specific real-world policy decisions. For proper policy evaluation, we would want to include all real-world complexities of electricity markets and emissions policies, and with these additional considerations, it is possible that the dynamics of allowance exchange rates could become counterintuitive. Additionally, we could adjust the parameters of the social welfare calculation, including the social cost of carbon, health benefits from criteria pollutants, and the incidence of these pollutants, to yield a robust set of modeling results relevant to specific policy discussions.

4. Conclusion

This paper provides a framework to analyze the linking of regional or sectoral emissions trading programs with different abatement opportunities and different features, including stringency as measured by allowance prices, and different price containment mechanisms. We develop an analytical framework for linking of emissions trading programs using an allowance exchange rate, which has the potential to align program stringency or price collars and can substitute for more direct efforts to harmonize program details before linking. We then apply that framework to simulate the potential linking of two carbon markets covering electricity sector emissions in the Western and Eastern United States.

Our analytical and simulation models demonstrate that formal linking of emissions trading systems with an allowance exchange rate may lead to aggregate emissions that differ from the sum of the caps of the two programs when they operate independently. We find two-way uncertainty to the emissions outcome of linking; that is, emissions can be either lower or higher under a linked market. The use of an exchange rate to reconcile differences in stringency between the programs can have the effect of changing aggregate emissions compared to autarky, and the most likely set of exchange rates will reduce emissions. This consequence of linking might become increasingly apparent if relative marginal abatement costs change over time, for example, due to changes in fuel prices or electricity demand. Another reason this uncertainty could result is the presence of price containment measures, either price floors or ceilings, that adjust the number of emissions allowances introduced in one program in response to allowance prices, but which have effects that propagate across both programs when they are linked. In addition, other aspects of program design that could lead to this outcome include the treatment of offsets or efforts to contain leakage, some of which have been anticipated previously in the literature.

Linking with an allowance exchange rate also has important implications for the economic costs of the trading systems. Our analytical model finds that traditional 1:1 linking improves the cost-effectiveness of emissions reductions, although the use of an exchange rate undoes some of these cost reductions and, in extreme cases, may even yield a linked system that is costlier that the combination of the independent systems. Because the exchange rate affects both emissions and cost-effectiveness, its choice has implications for the overall efficiency of the linked system, and in the core range of exchange rates between autarky and 1:1 exchange that are likely to be considered by policymakers, linking yields welfare gains. These welfare gains from linking accrue unequally throughout the linked system, however; some constituencies in each program may benefit greatly from linking, but others may incur large losses.

Increasing attention is also being given to the distribution of emissions reductions that result from carbon trading programs, and the distribution of costs that are incurred to meet the goals of these programs, despite the global nature of climate change. This attention is focused on the concern that not all communities see reductions in criteria air pollutants or receive other environmental benefits in equal measure, and some may be made worse due to the flexible implementation of emissions trading and other carbon pricing schemes. Additionally, some constituencies may bear disproportionate costs of emissions reductions, while other constituencies are poised to benefit greatly. Economic approaches to environmental policy typically separate these effects from the central goal of carbon pricing, which is to achieve greenhouse gas reductions at the least cost. In general, linking programs and expanding the coverage of programs is expected to contribute to this central goal. However, our research highlights other issues that should be anticipated, including changes in the total emissions of the regulated pollutant and potentially uneven distributional outcomes among the affected constituencies, but more generally would also include changes in conventional air pollutants. Policymakers may need to consider and compensate for these distributional effects if linking occurs.

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