# Linking Carbon Markets with Different Initial Conditions

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## Abstract

Linkage of emissions trading systems theoretically minimizes total abatement costs by allowing fungibility of emissions reductions across jurisdictions. We develop a theoretical framework to investigate the implications of linking systems with unique designs. We find that a uniform price is rarely socially optimal when linking bilaterally; instead, an allowance exchange rate, which results in different allowance prices in each trading system, yields a socially preferred outcome by bringing total abatement closer to the socially optimal level. This finding follows from the fact that an exchange rate can increase or decrease total abatement across the linked systems because one allowance does not correspond to one unit of emissions under an exchange rate. Over a core range of exchange rate, which policymakers may be most likely to consider, abatement and total welfare are greater in the linked system than in autarky. Other exchange rates, however, can erode the environmental benefits of the programs, driving down total abatement and driving allowance prices toward price floors. Thus, the choice of the exchange rate is important for environmental outcomes and the distributional outcomes across the linked systems. We also qualitatively assess the California and the Regional Greenhouse Gas Initiative systems, which we find to be nearly ready to link despite some differences in their initial conditions, including design and stringency. We use a simulation model of regional electricity markets to investigate market outcomes under such a linked system. We consider possible exchange rates for allowances to adjust for differences in program stringency, and we examine how they interact with price floors and ceilings while explicitly representing other program features (e.g., leakage policies, companion policies, and allowance allocation). We find that aggregate emissions and emissions in each jurisdiction change in ways predicted by theory but that efficiency gains can be distributed in nuanced and nonintuitive ways.

**Key Words:** greenhouse gas, climate change, climate policy, 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 57 international, national, regional, state, provincial and municipal carbon pricing or trading systems are in operation, instead of the single international carbon market that was once imagined (World Bank 2019). 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 system mutually allow their regulated firms to use emissions allowances from any of the linked jurisdictions to meet compliance obligations (Jaffe, Ranson, and Stavins 2009).[1] Recent policy discussions regarding the linking of trading systems have considered an allowance exchange rate, which denominates the value of an emissions allowance (i.e., the quantity of emissions per allowance) differently in each system. An exchange rate provides policy makers with a mechanism to better balance the costs and benefits of linking, which we discuss in detail below, and to align program characteristics that otherwise might prohibit systems from linking.

In this paper, we examine how an allowance exchange rate may be used to harmonize trading systems with different initial program conditions – in particular, program stringency and price collars – that otherwise may not be in a position to link. We develop a theoretical model of

[1] 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 Hates 2009; Lazarus et al. 2015), and multilateral linking (Doda, Quemin, and Taschini 2019).

a linked trading system to describe how an exchange rate affects overall efficiency and market outcomes, including distributional effects, in a linked market. We then take a closer look at the potential linking of the California and Regional Greenhouse Gas Initiative (RGGI) trading programs. We first discuss the readiness for these two systems to link. We then simulate the linking of these systems using a simulation model of regional electricity markets within the US, which characterizes the particular design features of each program, accounting for how they interact with their respective regional electricity markets.

Our theoretical model yields novel and non-intuitive results about linking trading systems with an exchange rate. Most importantly, we show that in real-world trading systems, a uniform price, or 1-for-1 linking, is rarely socially optimal when linking bilaterally. Trading programs often fail to equate the allowance price and the marginal damage of carbon emissions, so the second-best outcome is to forgo the allocative efficiency of a uniform price in favor of moving the linked programs closer to the socially optimal allowance price and level of abatement. This finding follows from the fact that an exchange rate can increase or decrease total abatement across the linked systems because one allowance does not correspond to one unit of emissions under an exchange rate. Over a core range of exchange rates, abatement and total welfare are greater in the linked system than in autarky. For most real-world systems, this range corresponds to the exchange rates most likely to be considered by policy makers because it spans from the 1-for-1 exchange rate that achieves allocative efficiency and is the point of departure for existing trading programs and the rate equal to the ratio of autarkic prices that results in no change from autarky. This range includes the social optimum, suggesting that well-designed linked systems can yield benefits for the environment and each trading systems. Other exchange rates, however, can erode the desired environmental benefits of the trading programs. These exchange rates drive down total abatement and drive allowance prices toward price floors, making price ceilings irrelevant for many linked systems. These results highlight that the choice of the exchange rate is important for environmental outcomes and the distributional outcomes across the linked systems.

Our qualitative analysis of the California and RGGI programs suggests that they are nearly ready to link; any misalignments in program features are either tolerable or relatively straightforward to align and, therefore, the programs could link quite easily in the future. Then, using the simulation model, we find that aggregate emissions and emissions in each jurisdiction change in ways predicted by theory but that efficiency gains can be distributed in nuanced and nonintuitive ways.

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 carbon price across the newly linked system that is expected to lower overall abatement costs. The potential efficiency gains 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, Doda, Quemin, and Taschini 2019, Burtraw et al. 2013). 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. 2015). 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 systems have required significant negotiations between jurisdictions in order to harmonize the design of the systems; the time and resources 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).[2] Moreover, linking can exacerbate allowance price volatility in certain cases (Doda and Taschini 2017). From an environmental perspective, linking could increase emissions leakage if allowance prices increase in the system that is more susceptible to leakage (Jaffe, Ranson, and Stavins 2009) and may alter incentives for cap setting, encouraging systems to set lower caps to achieve lower prices and therefore export more allowances, thereby resulting in higher emissions than would occur without linking (Bohm 1992, Helm 2003).

[2] 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.

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. Linking also might provide an incentive to introduce companion policies, such as technology support policies, that reduce local demand for allowances, in order 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 systems 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 (a selection of which are reviewed by Springer 2003, or the emissions outcomes of different coalitions of linked trading systems (e.g., 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 allowances (Fischer 2003, Lazarus et al. 2015)), 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 through the use of an allowance exchange rate, which denominates the value of an emissions allowance (i.e., the quantity of emissions per allowance) differently in each system. That is, an exchange rate mandates that an allowance from one system is worth more or less in terms of compliance (allowable tons per allowance) than is an allowance from another system. 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 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). Greenhouse gas allowance exchange rates have also been included in recent policy discussions, including efforts by the World Bank's Networked Carbon Market Initiative[3] (Macinante 2016) and China's stated intentions to discount allowances from regional emissions markets when its national trading system launches (Carbon Pulse 2015). Quemen and de Perthuis (2019) compare exchange rates with other mechanisms such as quantitative limits on trading and border adjustments as transitional mechanisms to guide

[3] 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 "harmonzing" climate actions so that units can be traded on a one-to-one basis.

heterogeneous programs towards cost effective outcomes. Linking with exchange rates 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).

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 systems are nearly identical in design. In reality, however, the array of existing systems exhibits various designs and stringencies. We complement the existing literature by evaluating the linking of systems that have various and different designs (i.e., explicitly different price floors and ceilings and potentially multiple price steps, allocation methods, leakage policies and cap ambition and implicitly different offset and companion policies) and considering how different design parameters interact with alternative architectures for linking (e.g., different exchange rates for allowances). In particular, we make two primary contributions with this work. First, we develop an analytical model that formalizes the economic implications and emission market outcomes of linking, both with and without an exchange rate. This model yields novel findings on the results of linking emission markets, as well as the formalization of results that had previously been described only qualitatively. Second, we test several of our theoretical results and illustrate other important market outcomes of linking by simulating a link between the California and Regional Greenhouse Gas Initiative (RGGI) trading programs. We use a simulation model of regional electricity markets within the US in order to characterize the particular design features of California's and RGGI's programs, accounting for how they interact with their respective regional electricity markets. We simulate the trading programs under autarky (when they are independent) and under various exchange rates. The electricity market model allows us to consider a wide range of economic 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. An Analytical Model of Linking

The model considers a regional economy with production supplied by a representative firm. We first show how this representative firm responds when faced with a $CO_2$ policy that imposes a price on $CO_2$ emissions. We next describe the equilibrium outcomes of an emissions trading market 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.

This model describes the linking of two trading systems at the subnational or national level. In discussion we explain that the 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 system with a price floor that is coincident with a price ceiling.[4]

### *Production*

The production sector in a region 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, $E$:

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

The parameters $\alpha$, $\beta$, and $\gamma$ are region-specific and depend on the quantity of output produced and the firm's production technology, both of which we assume to be fixed over the time horizon considered;[5] we further assume $\alpha, \beta, \gamma > 0$. With no carbon policy in place, this firm would minimize 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 would deviate from this 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 $C(A) = G(\bar{E} - A) - G(\bar{E})$, which yields:

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

Each unit of abatement also reduces the firm's cost of policy compliance by $p$. Under this emissions price the firm selects the level of abatement that minimizes its total cost:

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

This optimization problem yields the first-order condition:

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

[4] Metcalf and Weisbach (2012) consider linking between a cap and trade system and a carbon tax.

[5] Our simulation results focus on the electricity sector and introduce price-responsive electricity demand, but the market equilibria show small changes in the retail price of electricity and the quantity of electricity consumed, which is roughly consistent with this assumption that a fixed quantity of output is demanded.

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

### *Emissions Trading in Autarky*

We now consider the specific design of the emissions trading system and the resulting outcomes – allowance prices and abatement – that occur in this market in autarky. Although an emissions trading policy has many design parameters through which the system can be adjusted, this analytical model focuses on two, and arguably the most important, of these policy parameters: the level of the cap and the cost containment mechanism.

The intended emission 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 $CO_2$. These allowances are auctioned in a multi-unit, uniform-price auction. [6] This auction has a reserve price of $p^F$, known as a price floor, below which no allowances will be auctioned. Additional allowances beyond the intended cap are also available for purchase at a price of $p^C$, which is known as the price ceiling.

Combining these policy parameters with the firm's first-order condition yields the resulting allowance price and level of abatement:

$$(p^0, A^0) = \begin{cases} \left(p^F, \dfrac{p^F}{\gamma}\right) & \text{if} \quad p^F > \gamma\bar{A} \\ (\gamma\bar{A}, \bar{A}) & \text{if} \quad p^F \leq \gamma\bar{A} \leq p^C \\ \left(p^C, \dfrac{p^C}{\gamma}\right) & \text{if} \quad p^C < \gamma\bar{A} \end{cases}$$

[6] In many emissions trading systems, some allowances are freely allocated to emitters or other agents for political or economic reasons, such as building political support for the trading system 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 purchased in the auction, which will yield an allowance price below the auction 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. Systems 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 if a price floor exists it is enforced, as in California's $CO_2$ trading program (Burtraw and McCormack 2017).

where the 0 superscript indicates outcomes under autarky. In words, if the price floor is set relatively high or the required level of abatement is relatively low, the price floor binds and fewer emissions allowances are introduced than described by the policy.[7] As a result, emissions are less – and abatement is greater – than that specified by the policy's emissions cap. Conversely, if the price ceiling is set relatively low or the required level of abatement is relatively high, the price ceiling binds and emissions are greater – and abatement is less – than that specified by the policy. In all other cases, the specified emissions cap is achieved with the specified level of abatement, and the allowance price depends on $\gamma$, the slope of the firm's marginal abatement cost curve.

### *Linked Emissions Trading*

We now consider two independent emissions trading systems, denoted by subscripts $i$ and $j$, that link through the trade of emissions allowances. All characteristics of the representative firm – such as the cost function and the quantity of output – and characteristics of the policy – such as allowances issued and price collars – can vary across the different systems. Emitters in each system can comply with the emissions trading system by holding allowances issued by either system, but allowances are traded between the systems at an agreed exchange rate.

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

We assume there are no arbitrage opportunities across the systems, so the price of an allowance from system $i$ is $r$ times the price of an allowance from system $j$, $p_i = rp_j$.[8] We also

[7] There are several reasons why the design of the emissions trading system might yield prices at the price floor or price ceiling, which we abstract away from in this theoretical 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 supress prices. Additionally, policymakers may face many poltitical constraints when designing a trading system, and in trying to balance competing demands, an allowance price at the floor or ceiling may be the only politically feasible outcome.

[8] 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.

assume price collars do not bind in either system under autarky, as a binding price collar suggests the policy is constrained by political considerations that would also restrict linking.

This linking of the trading systems and the chosen exchange rate have important implications for the resulting allowance prices, abatement, and overall welfare.

**Allowance Price Collar**

We first show how the exchange rate determines the effective price collar faced by the linked market. We express the price collar in terms of system $i$ allowances; the price collar for system $j$ allowances is $\frac{1}{r}$ times these prices.

**Result 1.** The exchange rate, $r$, determines the linked price collar:

i. If $r \leq \frac{p_i^F}{p_j^F}$, then $p^F = p_i^F$; if $r \geq \frac{p_i^F}{p_j^F}$, then $p^F = rp_j^F$.

ii. If $r \geq \frac{p_i^C}{p_j^C}$, then $p^C = p_i^C$; if $r \leq \frac{p_i^C}{p_j^C}$, then $p^C = rp_j^C$.

In words, when the exchange rate is sufficiently low, the price floor of system $i$ determines the linked price floor; whereas, when the exchange rate is sufficiently high, the price floor of system $j$ determines the linked price floor.[9] Conversely, the price ceiling of system $i$ determines the linked price ceiling when the exchange rate is sufficiently high, and the price ceiling of system $j$ determines the linked price ceiling when the exchange rate is sufficiently low.[10] This result yields several additional conclusions relating to the effective price collar in a linked market.

First, the price collar each system faces in a linked market will always be weakly tighter than the price collar under autarky, with more extreme exchange rates yielding tighter price collars. In fact, if the exchange rate is set at $r = \frac{p_i^F}{p_j^C}$ or $r = \frac{p_i^C}{p_j^F}$, the price collar is tightened to the maximum extent possible, with the price floor and price ceiling coincident and the linked market effectively facing a carbon tax.

[9] For example, if the exchange rate is $r$=1 and $p_i^F \geq p_j^F$, then the effective price floor in system $i$ is $p_i^F$.

[10] These results hold for a hard price collar that has no limit on the number of additional allowances sold at the price ceiling. With a soft price collar, which limits the number of allowances available at the price ceiling, the linked price ceiling may rise above this soft price ceiling if there is sufficient demand for allowances to exhaust the number supplied at the soft price ceiling.

The second conclusion stems from the practical consideration that a feasible market must have a price floor that is weakly below the price ceiling. To ensure this condition is met, the exchange rate must be in the interval $\frac{p_i^F}{p_j^C} \leq r \leq \frac{p_i^C}{p_j^F}$. If the exchange rate is below this interval ($r < \frac{p_i^F}{p_j^C}$), the price collar is composed of system $i$'s price floor and system $j$'s price ceiling, but the value of the floor is greater than the value of the ceiling (in terms of system $i$ allowances, $p_i^F > rp_j^C$). Similarly, if the exchange rate is set above this interval ($r > \frac{p_i^C}{p_j^F}$), the linked market again has no feasible allowance price.

**Allowance Prices and Abatement**

With the linked price collar defined, we next consider the resulting allowance prices and abatement when the price collar is not binding. In this case, there is no shortage or surplus of allowances in the linked market. Total abatement is not necessarily equal to that under autarky, however, because the systems are linked with an exchange rate. Each allowance traded from system $i$ to system $j$ reduces emissions by one unit in system $i$ and increases emissions by $r$ units in system $j$. That is, at the linked market equilibrium, the following expression must hold:

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

Combining the firms' first-order conditions ($p_i = \gamma_i A_i$) and the assumption of no arbitrage opportunities ($p_i = rp_j$) further gives:

$$\gamma_i A_i = r\gamma_j A_j$$

Using these two expressions, we solve for the level of abatement in system $i$ in the linked market:

$$A_i = \frac{\bar{A}_i + \frac{1}{r}\bar{A}_j}{1 + \frac{\gamma_i}{r^2\gamma_j}}$$

We again use the firm's first-order condition, in order to solve for the allowance price in system $i$ in the linked market:

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

We can similarly solve for the abatement and allowance price in system $j$ in the linked market:

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

These expressions have an intuitive interpretation. For example, the allowance price that results in system $i$ in a linked market is the product of total abatement required by the two systems and the slope of the horizontally summed marginal abatement cost curve, if the parameters for system $j$ are converted to their system $i$ equivalents.[11]

Figure 1 plots how allowance prices (top panel) and abatement (bottom panel) vary with the exchange rate for a particular set of parameters, ignoring price collars.[12] Of particular interest is the fact that each system's allowance price and the total abatement is a non-monotonic function of $r$ that reaches a global maximum, meaning there is a maximum allowance price that can result in each system and a maximum level of total abatement that can be achieved between the two systems.

[11] The numerator ($\bar{A}_i + \frac{1}{r}\bar{A}_j$) is the sum of abatement required by the two policies if system $j$'s required abatement is converted to its system $i$ equivalent using the exchange rate. The denominator ($\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}$) is the inverse of the slope of the summed marginal abatement cost curves if system $j$'s curve is converted to its system $i$ equivalent using the exchange rate. Note that abatement, $A$. is in units of tons, so $r$ is used to convert between the two systems. However, the slope of the marginal cost curve, $\gamma$, is in units of $\$/\text{ton}^2$, so $r^2$ is used to convert between the two systems.

[12] To generate this figure, we used the following parameters: $\bar{A}_i = 100$, $\gamma_i = 0.1$, $\bar{A}_j = 200$, $\gamma_j = 0.1$. Results are qualitatively similar for any set of parameters.

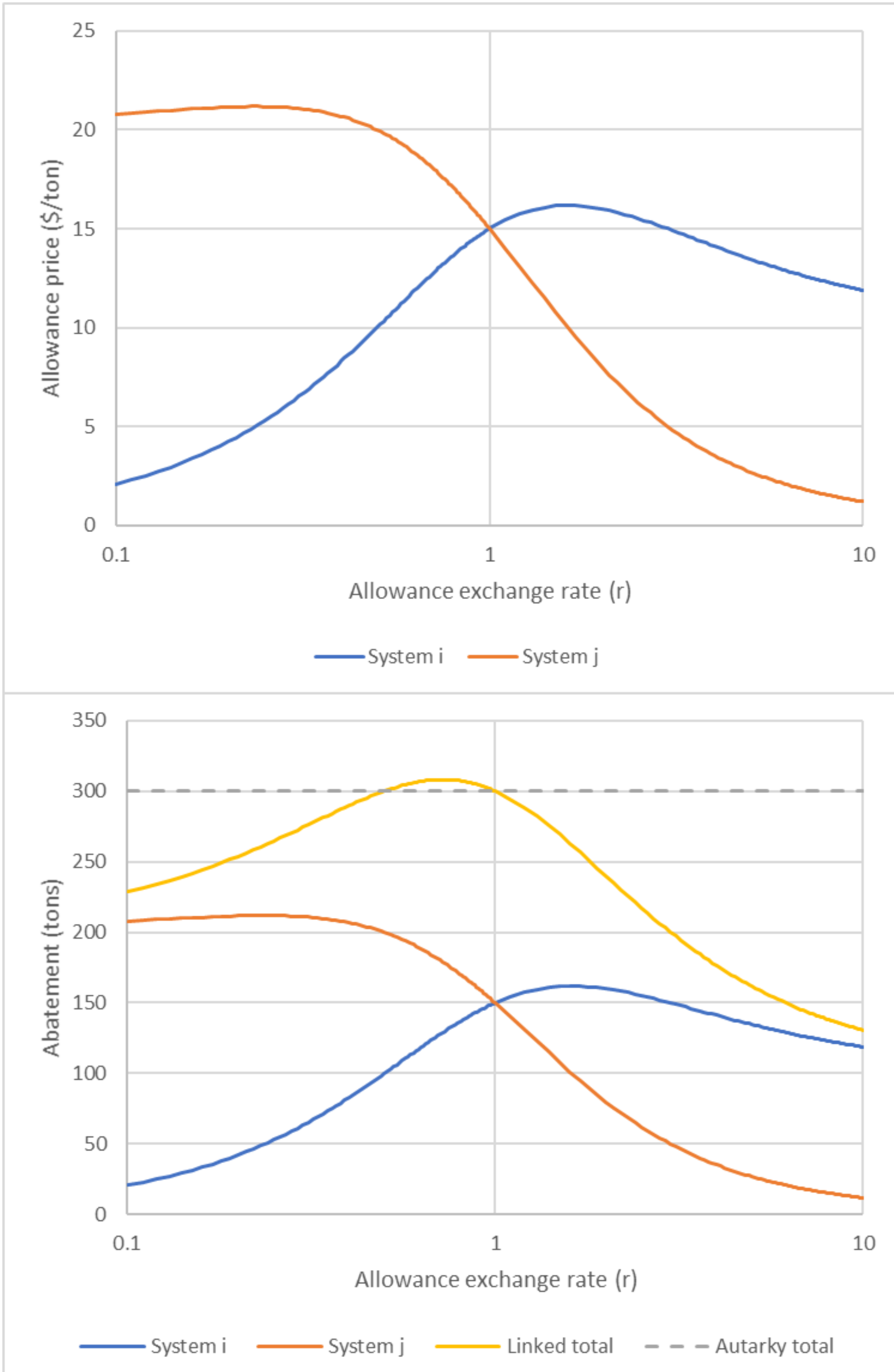


**Figure 1: Allowance Prices and Abatement**

Using the above expressions for allowance prices when the price collar does not bind, we next show how the choice of exchange rates determines if the linked market is at a price floor, price ceiling, or within the price collar. We begin by considering a linked market in which system $i$'s price floor is binding. This only occurs if the allowance price in system $i$ would otherwise have been below the price floor. That is:

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

Solving for $r$ gives an exchange rate of:

$$r \leq \frac{-\bar{A}_j + \sqrt{\bar{A}_j^2 + 4\left(\bar{A}_i - \frac{p_i^F}{\gamma_i}\right)\left(\frac{p_i^F}{\gamma_j}\right)}}{2\left(\bar{A}_i - \frac{p_i^F}{\gamma_i}\right)}$$

We similarly solve for the exchange rates that yield the other price collar outcomes. This gives our second result, which is how the exchange rate determines whether this linked price collar is binding and the resulting market outcomes: allowance price in system $i$, $p_i$; allowance price in system $j$, $p_j$; and total abatement, $A_i + A_j$.

**Result 2.** The exchange rate, $r$, determines the linked market outcome:

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

ii. If $\frac{\bar{A}_i - \sqrt{\bar{A}_i^2 - 4\left(\frac{p_j^C}{\gamma_i}\right)\left(\frac{p_j^C}{\gamma_j} - \bar{A}_j\right)}}{2\frac{p_j^C}{\gamma_i}} \leq r \leq \frac{\bar{A}_i + \sqrt{\bar{A}_i^2 - 4\left(\frac{p_j^C}{\gamma_i}\right)\left(\frac{p_j^C}{\gamma_j} - \bar{A}_j\right)}}{2\frac{p_j^C}{\gamma_i}}$, then the price ceiling of system $j$ binds and $(p_i, p_j, A_i + A_j) = \left(rp_j^C, p_j^C, \left(\frac{r}{\gamma_i} + \frac{1}{\gamma_j}\right)p_j^C\right)$.

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

iv. If $r \geq \frac{\bar{A}_i + \sqrt{\bar{A}_i^2 + 4\left(\bar{A}_j - \frac{p_j^F}{\gamma_j}\right)\left(\frac{p_j^F}{\gamma_i}\right)}}{2\frac{p_j^F}{\gamma_i}}$, then the price floor of system $j$ binds and $(p_i, p_j, A_i + A_j) = \left(rp_j^F, p_j^F, \left(\frac{r}{\gamma_i} + \frac{1}{\gamma_j}\right)p_j^F\right)$.

v. Otherwise, the linked market clears inside the price collar and $(p_i, p_j, A_i + A_j) = \left(\frac{\bar{A}_i + \frac{1}{r}\bar{A}_j}{\frac{1}{\gamma_i} + \frac{1}{r^2\gamma_j}}, \frac{r\bar{A}_i + \bar{A}_j}{\frac{r^2}{\gamma_i} + \frac{1}{\gamma_j}}, \left(\frac{r\bar{A}_i + \bar{A}_j}{\frac{r^2}{\gamma_i} + \frac{1}{\gamma_j}}\right)\left(\frac{r}{\gamma_i} + \frac{1}{\gamma_j}\right)\right)$.

In words, if the exchange rate is sufficiently low, then the market clears at the price floor of system $i$.[13] Relative to autarky, this yields a lower allowance price and less abatement in system $i$, but a higher allowance price and more abatement in system $j$. Thus, the effect on total abatement of linking within this interval of exchange rates is ambiguous; however, lower exchange rates correspond to greater levels of total abatement in the linked market when the price floor of system $i$ binds. Conversely, if the exchange rate is set sufficiently high, then the market clears at the price floor of system $j$ and the effects of linking are the reverse of the effects at system $i$'s price floor.

There are also intervals of exchange rates that, in theory, result in the market clearing at a price ceiling, as defined above. The nature of the linked market, however, moderates high allowance prices and effectively imposes an additional price ceiling.[14] As shown in Figure 1, when the linked price collar does not bind, each system has a maximum allowance price that can

[13] It is possible, depending on the parameters of each system, for this or any of the exchange rate intervals in Result 2 to fall outside the feasible set of exchange rates (i.e., $\frac{p_i^F}{p_j^C} \leq r \leq \frac{p_i^C}{p_j^F}$) 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). It can be shown, however, that this overlap only occurs outside the feasible set of exchange rates, so each exchange rate within the feasible set yields only one of the outcomes given in Result 2.

[14] Linking without an exchange rates moderates both high and low allowance prices by equating allowance prices in the linked systems. Using an exchange rate, however, introduces a wedge between these prices, which tends to drive prices down. The system with the lower price imports allowances from the higher-priced system, but each allowance corresponds to more emissions in the lower-priced system in most cases, so total abatement decreases across the linked system. This lower level of abatement corresponds to lower allowance prices. For a small range of exchange rates, the opposite effect occurs and abatement increases, corresponding to higher allowance prices. But there are limits to how much abatement, and hence allowance prices, can increase through linking.

result from the linked market, regardless of either policy's price ceiling.[15] If this maximum price is below the system's price ceiling, then the price ceiling is superfluous and will never bind. In fact, unless one system's autarkic allowance price is relatively close to its price ceiling, this implicit price ceiling will restrict the linked market from reaching either system's explicit price ceiling. 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.

If the exchange rate does not lead the market to a price floor or price ceiling, the allowance prices and total abatement are as defined in (v) above and depend importantly on how the exchange rate compares to the ratio of autarkic prices, $\frac{p_i^0}{p_j^0}$.[16] When $r = \frac{p_i^0}{p_j^0}$, allowance prices and abatement are equal in the linked market and in autarky. When $r > \frac{p_i^0}{p_j^0}$, the allowance price and abatement in system $i$ are greater in the linked market than in autarky, and the allowance price and abatement in system $j$ are less in the linked market than in autarky. When $r < \frac{p_i^0}{p_j^0}$, the effect of linking is the reverse.

In other words, when not bound by the price collar, the effect of linking is to weakly increase abatement in one system and weakly decrease abatement in the other. The exchange rate determines the relative size of these individual effects and the effect on total abatement. For example, each additional unit of abatement in system $i$ frees up an allowance for use in system $j$, where each allowance corresponds to $r$ units of abatement. The effect of linking on abatement in system $j$ is $r$ times greater than that in system $i$. Thus, when the price collar is not binding, the choice of the exchange rate determines whether total abatement in the linked market is greater or less than under autarky; the effect of linking is to increase total abatement when the exchange

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

[16] Lazarus et al. (2015) discuss the impact of varied exchange rates of economic effectiveness and emissions outcomes using a model with policies and linear marginal abatement cost curves parametrized by specific values. We generalize this work by considering arbitrary parameters and extend the analysis by introducing a price collar.

rate is in the open interval bounded by 1 and $\frac{p_i^0}{p_j^0}$.[17] This same interval is the most likely to be relevant to policymakers. An exchange rate of 1, which maximizes allocative efficiency, and an exchange rate of $\frac{p_i^0}{p_j^0}$, which yields results equal to autarky, are natural starting places for policymakers negotiating an exchange rate, so an outcome within this range seems most likely.

**Optimal Exchange Rate**

This fact – 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 allocative efficiency is achieved when the exchange rate is set at $r = 1$, so allowance prices are equalized and all emitters face the same marginal incentive to abate. 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 allocative efficiency 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 system's price collar, level of abatement, and marginal abatement cost curve are fixed, so the only choice variable is the exchange rate. We further assume the interval of exchange rates that yield an interior solution is sufficiently large to include the optimum. 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 marginal net benefit of abatement in system $i$ and $\frac{\partial A_i}{\partial r}$ is the marginal quantity of abatement in system $i$ with respect to the exchange rate, so the product is the marginal net benefit 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 this marginal benefit across the two linked systems.

From this first-order condition, we see that an exchange rate of $r = 1$ is optimal when the linked market price is equal to the marginal damage of emissions, $p_i = p_j = d$. If an exchange

[17] That is, $1 < r < \frac{p_i^0}{p_j^0}$ when $\frac{p_i^0}{p_j^0} > 1$ and $\frac{p_i^0}{p_j^0} < r < 1$ when $\frac{p_i^0}{p_j^0} < 1$.

rate of 1 yields a linked allowance price that is below $d$, however, then social welfare may 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 may be improved with an exchange rate that decreases abatement. Solving for the optimal exchange rate gives our final result.

**Result 3.** The socially optimal exchange rate is[18]

$$r = \frac{\gamma_i\left(\bar{A}_i(2d - p_i^0) - \bar{A}_j(2d - p_j^0)\right) + \gamma_i\sqrt{(\bar{A}_i p_i^0 + \bar{A}_j p_j^0)\left(\bar{A}_i p_i^0 + \bar{A}_j p_j^0 + \frac{4d}{\gamma_i}(d - p_i^0) + \frac{4d}{\gamma_j}(d - p_j^0)\right)}}{2\left(d(p_i^0 + p_j^0) - p_i^0 p_j^0\right)}$$

It can be shown that 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 marginal damage of emission, $p_i = p_j = d$.[19] This is the first-best solution, resulting in both allocative efficiency between the two systems and the efficient level of total abatement. This scenario, however, is unlikely to occur when linking real-world trading systems.

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 systems with equal autarkic allowance prices simply yields the same outcomes as autarky, so it is not clear why those trading systems would link. Thus, we conclude that with nearly all real-world trading systems, social welfare is maximized when linking occurs at a rate other than $r = 1$.

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

[19] This 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 (i.e., $p_i^0 = p_j^0 < d$), there is no ability to trade off allocative efficiency for additional abatement; instead, deviating from $r = 1$ both reduces allocative efficiency and moves the linked system further away from the optimal level of abatement. Even in the case of the systems 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.

If an exchange rate of 1 yields a linked system with too little abatement – that is, the linked allowance price is below marginal damages – then the socially optimal exchange rate lies within the open interval bounded by 1 and $\frac{p_i^0}{p_j^0}$. As discussed previously, this interval corresponds to the exchange rates most likely to be considered by policymakers, indicating that many linked systems may achieve outcomes close to the social optimum.

**Distributional Effects**

Policy makers may be interested not in setting the exchange rate to be socially optimal globally, but rather to benefit their own government, constituents, or region as a whole. To this end, in our final result, we show how linking and the choice of the exchange rate differently affects several metrics in each system. We consider only results that yield prices inside the price collar, not at the price floor or price ceiling.

We first consider the revenue raised by the regional government through the allowance auction, which for system $i$ is:[21]

$$GR_i = p_i(\bar{E}_i - \bar{A}_i)$$

We next consider the net flow of allowance revenues into or out of a system. The net revenue flow into system $i$ is:

$$NRF_i = p_i(A_i - \bar{A}_i)$$

We also consider the surplus earned by producers in each system. We assume output prices and quantities are fixed, so our measure of producer surplus is the negative of total cost, which is the sum of abatement cost and compliance cost. For system $i$ this producer surplus is:

$$PS_i = -p_i\left(\bar{E}_i - \frac{1}{2}A_i\right)$$

We finally consider total surplus in each system, which is equal to the sum of government revenues and producer surplus, which for system $i$ is:

$$TS_i = p_i\left(\frac{1}{2}A_i - \bar{A}_i\right)$$

Government revenue, net revenue flow, and total surplus increase as the allowance price – and thus also the level of abatement – increases, whereas producer surplus decreases as the

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[21] This and subsequent equations are equivalent in system $j$, other than the subscript.

allowance price and level of abatement increase. Combining these outcomes with Result 2 yields our final result.

**Result 4.** The exchange rate, $r$, determines the distributional effects of linking:

i. If $r > \frac{p_i^0}{p_j^0}$, linking increases (decreases) system $i$'s ($j$'s) government revenue, net revenue flow, and total surplus but decreases (increases) system $i$'s ($j$'s) producer surplus.

ii. If $r < \frac{p_i^0}{p_j^0}$, linking decreases (increases) system $i$'s ($j$'s) government revenue, net revenue flow, and total surplus but increases (decreases) system $i$'s ($j$'s) producer surplus.

This result is likely to have important implications for the exchange rates that policy makers are willing to implement given the political economy they face. For example, like-minded policy makers will not find a mutually agreeable exchange rate because effects on each region are exact opposites. Instead, when considering these metrics, the linking of trading systems will be mutually beneficial only when policy makers have different objective functions, such as one group of policy makers seeking to maximize its government revenue and the other seeking to maximize producer surplus within its jurisdiction.[22]

## 3. Evaluating Readiness to Link – The Case of California and the Regional Greenhouse Gas Initiative

In this section, we evaluate the readiness of the California and RGGI emissions markets for linking and set the stage for an application of the analytical model.[23] Many studies point to the significant obstacles in linking two trading systems that are designed separately and the potential costs of linking without close harmonization of specific design features (Haites and Wang 2009, Zyla 2010). Burtraw et al. (2013) conduct an extensive evaluation of the design features of the California and RGGI systems, finding that the designs are already quite closely harmonized because of a long history of cooperation, information sharing, mutual learning, and replication of each other's designs. The authors conclude—based on criteria including the degree to which design features are aligned, and whether any misalignments of design features would be important for the functioning of a new enlarged allowance market or for political reasons stemming from

[22] These implications are true when outcomes are certain. Doda and Taschini (2017) and Doda, Quemin, and Taschini (2019) introduce uncertainty and show that mutually beneficial links can exist, but they do not consider the role of exchnage rates in linking.

[23] This task is made somewhat easier because the RGGI program is limited to the electricity sector, and many design features of both programs are similar in this sector.

economic or environmental preferences—that the California and RGGI trading systems are nearly ready to link. The discussion below focuses on four design features identified by Burtraw et al. (2013). We find that misalignments regarding these four features are either tolerable or relatively straightforward to align, and therefore that the programs could link quite easily in the future.

### *Comparability of the Emissions Cap*

The main determinant of the stringency of the program and of allowance prices is the choice of how many allowances to issue (the emissions cap). RGGI allowances are denoted in short tons while California allowances are denoted in metric tons. This distinction is not a barrier to linking the markets but it implies that, unless one of the programs changes its unit of measurement, linking will require a conversion factor between the programs to achieve equivalent tons. Current allowance prices vary widely between RGGI (near $5 per short ton) and California (about $17 per metric ton), indicating large potential gains in the efficiency of overall emissions reductions. We consider all calculations in this paper in short tons.

Linking also implies flows of allowances between regions. Generally, the region with lower stringency is expected to export allowances, and therefore import revenue from the region with higher stringency. Such transfers potentially present a political challenge but do not present a challenge to the functioning of the enlarged allowance market. Nonetheless, the choice of stringency in a linked market must be balanced against the distributional outcome across and within systems.

An exchange rate offers a possible solution for regulators sensitive to concerns about revenue transfers associated with inter-regional allowance flows. For example, an exchange rate might specify that three RGGI allowances are equivalent to one California allowance—meaning a California entity could retire one California allowance or three RGGI allowances for one ton of emissions, and a RGGI entity could retire one California allowance or three RGGI allowances for three tons of emissions. This exchange rate is similar to the ratio of prices observed in the two programs. In principle, an exchange rate would allow a jurisdiction to balance the cost savings achieved by linking with political preferences, such as more localized control over allowances prices and wealth transfers.[24] However, as demonstrated in the analytical discussion in section 2 above and in the simulation model in section 4 below, the use of exchange rates would introduce

[24] As programs evolve, the political acceptability of higher allowance prices may change, enabling an adjustment in the exchange rate through mandated, periodic reevaluation of the exchange rates, through automatic adjustments of the exchange rate via a pre-specified adjustment schedule, or indexed to an economic or environmental indicator.

uncertainty regarding overall emissions. To address this uncertainty the trading program might employ numerous other mechanisms to control allowance flows such as import quotas, unilateral linking, discount rates, and fees imposed on using allowances from other programs for compliance (Mehling and Haites 2009) (Lazarus et al. 2015). We therefore argue there are a variety of tools available that enable jurisdictions to control allowance flows and consequently a large difference in allowance prices pre-link need not be an insurmountable barrier to linking.

### *Offsets*

If linked jurisdictions have different restrictions placed on the use or eligibility of offset credits, the price of offset credits will be communicated between jurisdictions through the linked allowance market. This feature is described as the "free-up effect" and is expected to occur if offset rules are not aligned across jurisdictions (Sterk and Kruger 2009, p. 396) The free-up effect results in rules in one jurisdiction unilaterally increasing the supply of compliance instruments in the linked market; for example, if one program allowed the use of a particular type of offset while the other program intended to preclude its use. A jurisdiction may wish to preclude the use of specific offset types if it prefers a high carbon price or if it is risk averse with respect to the environmental integrity of the offset credits. These preferences are subverted if programs with varying standards are linked, leading some authors to identify misaligned offset rules as a key barrier to linking (Tuerk et al. 2009, Sterk and Kruger 2009, Flachsland, Marschinski, and Edenhofer 2009). A discriminating program might impose import quotas, fees, or discount rates on offsets depending on their origin. This treatment would not solve the free-up effect, because the offsets would still be available in the other program, but it would ensure that they are not used for compliance in the discriminating program, which may help achieve political objectives. Because the free-up effect cannot be completely mitigated, regulators should place a high priority on aligning policies about offsets.

The RGGI and California programs currently have substantial overlap in the types of activities that can produce offsets, although the fact that RGGI is limited to electricity while the California program is broader means that some activities that can generate offsets in RGGI could be covered under California's program (such as use of natural gas for home heating). Each program does allow offsets from investments to reduce some non-CO2 gasses such as reducing methane emissions from agriculture as well as emissions reductions from afforestation. However, there are other differences in offset protocols that should be considered in a linking discussion.

### *Price Collars*

Marginal costs of compliance are determined primarily by the relative stringency (cap) of the individual programs and, as discussed above in section 2, price collars provide a method of managing costs when factors affecting the market are uncertain. However, different trigger prices for the floor and ceiling across linked systems could influence allowance flows and prices (Tuerk et al. 2009) and there also is a strong potential for differing floors to erode the environmental integrity of the linked programs as we discuss in section 2. If they are not aligned, linking could undermine the value of previous investments and thereby the confidence of investors going forward. Hence, the alignment of price floors and ceilings across programs poses a potential threat to the functioning of the market and is a focus of the modeling exercise in section 4.

One specific element of price collars poses a political and environmental challenge as well: whether additional allowances that might be available at a price ceiling come from "inside" or "outside" of the cap. In California, additional allowances come from under the cumulative cap through 2020. In RGGI allowances that are available at a price ceiling come from outside the cap. From a design standpoint, some advocates are likely to feel that environmental integrity, in the form of emissions reductions, can be guaranteed only if allowances come from under the cap (Harrison 2006).

### *Legal Contingencies*

Provisions for changing the design of either program or for delinking are difficult to align and potentially important. Within RGGI, each state retains the ability to leave the program, leading to a strong emphasis on finding consensus on policy decisions (Pizer and Yates 2015). This process within RGGI places it on a different decision-making schedule than that of California. Consequently, if formal linking were to occur, future changes to the combined program might be made unilaterally and on inconsistent time schedules.

The California Air Resources Board staff anticipates that if delinking were to occur, it would trigger a program review, as would be likely in RGGI as well. As predictable as the triggering of a review might be, the outcome is not. This element of uncertainty means compliance entities will recognize some risk associated with compliance instruments issued by the other jurisdiction. In particular, one is not likely to see banking of compliance instruments from the other jurisdiction. This failure to bank might imply a price difference in the market due to the different convenience yield that each instrument provides an investor, with some loss of market efficiency as a result, however, the technical issues associated with potential delinking are not likely to be fatal to the market. For example, on the date the decision to delink is announced, holdings of allowances from outside a given program are noted and those allowances assigned legitimacy for compliance (possibly within a limited period) or sold to the originating program (Haites and Wang 2009). This protocol was followed when New Jersey left RGGI in 2011; previously issued allowances from New Jersey that were banked were recognized as valid within RGGI. The departure of Ontario from the Western Climate Initiative trading program that involves California and Quebec followed a similar protocol – all compliance instruments in accounts registered in California or Quebec remained valid for compliance purposes and for trading. If that were not the protocol, one would not be likely to see banking of compliance instruments from the other jurisdiction. Alternatively, Newell et al. (2012) suggest a pegged currency system with separate currencies rather than a currency union. As long as linked trading systems maintain distinct units of account, which we interpret to include distinct registries, then they argue delinking should not be a problem.

## 4. Modeling Analysis of Linking the California and RGGI Markets

We now turn to our simulation of a link between the California and RGGI systems. We break this section into several parts: a short description of the model, a presentation of model results for both systems under autarky, and a discussion of our results under linked scenarios with different exchange ratios. We consider the effects of linking architecture (i.e., different exchange rates) and the unique designs of these two programs on several indicators of allowance market, electricity market, and emissions outcomes, as well as how different constituencies in the two regions are affected by the linking of the programs.

### Model Description

We use the Haiku electricity market model to explore the implications of linking the California and RGGI trading systems. The model simulates investment and retirement decisions and system operation in 22 inter-connected regions spanning the continental United States over a 25-year horizon.[25] We focus on results after roughly five to ten years, which gives program outcomes for a medium-run timeframe. Because these trading systems are represented within a national framework, changes in electricity generation and fuel use within these regions can have effects across the nation. However, because of geographic distance, there is no effective power flow between these regions so for general purposes it is sufficient to imagine that these electricity

[25] For more information about the RFF Haiku model, see Paul (Paul, Burtraw, and Palmer 2009).

markets operate independently, except when we link their emissions trading systems. Our analysis focuses on the electricity sector, so we limit our modeling to the electricity portion of the California program; our model covers the continental US, so we assume no relationship between California and the Quebec program.[26]

### *Results for the Unlinked Programs*

The California program, as modeled, results in emissions reductions from the electricity sector of roughly 10 percent below baseline levels with an allowance price of $14.2 per ton,[27] about 12 percent above the price floor (in short tons). The program raises electricity prices by about 2 percent and lowers REC prices by about 16 percent compared with a baseline with no program.

In our model, the RGGI region has an allowance price of $7.2 per ton. Emissions are 22 percent lower than a baseline with Phase 1 RGGI program specifications, under which allowances continue to be sold at the current price floor. The tightening of the RGGI cap results in only a minimal change in electricity price in the region, however, to the extent leakage occurs it will cause the overall emissions reduction to be less than we report for RGGI.

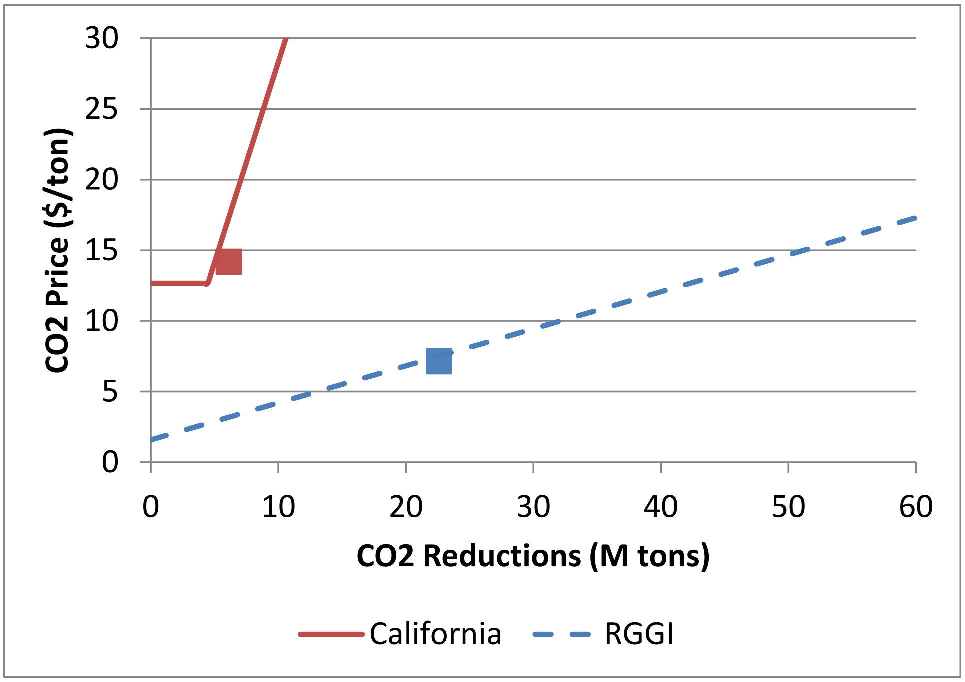
Figure 2 depicts estimated marginal abatement cost curves for the two regions and includes box points indicating the allowance price and level of reductions obtained in each of the unlinked programs relative to the modeled baseline.[28]

[26] See the appendix for additional details on how we incorporate the California and RGGI programs into our simulation model.

[27] All prices are in 2009 dollars per short ton.

[28] For each region, the marginal abatement cost curve was constructed from the pairs of allowance price and level of reductions in that region obtained over several model scenarios, including ones not reported here. The depicted curve is the best linear fit of these price-reduction pairs; the flat portion of California's curve represents the price floor in that market. The resulting marginal abatement cost curve does not perfectly align with the results of each scenario, but rather it represents the average over all modeling scenarios. Changes in the costs of renewable technologies and expanded availability of natural gas has affected the marginal abatement costs significantly since the timeframe for this modeling excercise but the findings about linking remain fully relevant.

**Figure 2. Marginal Abatement Cost Curves and Results for Unlinked Programs**

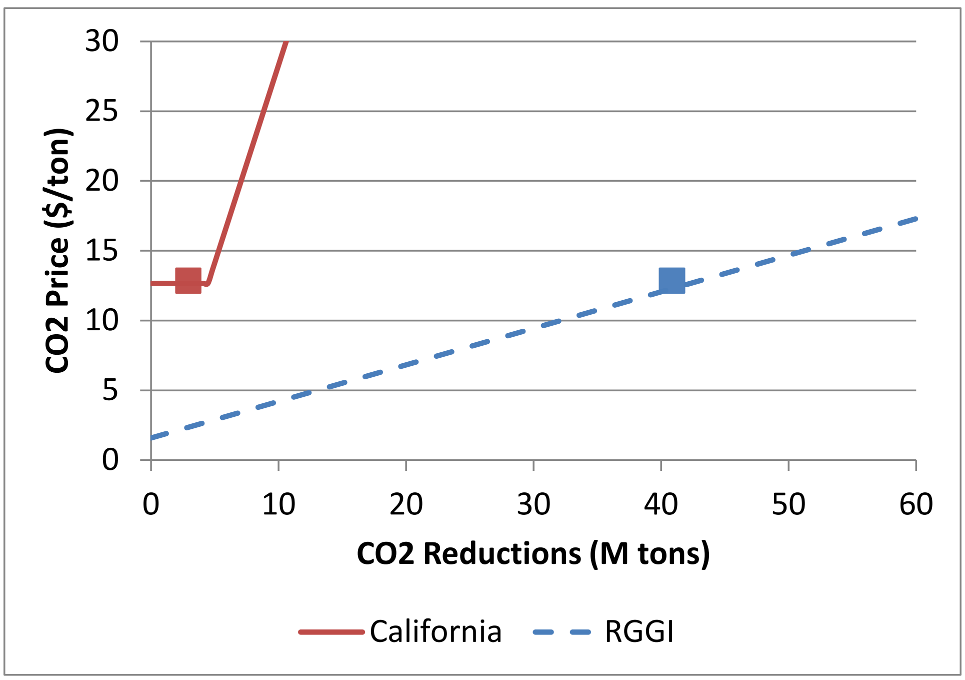



### *Results of One-for-One Linking*

In order to explore exchange rates as a possible linking architecture, we simulate a scenario that allows for one-for-one trading of allowances between the two programs (an exchange rate of 1:1) and another that allows for three-for-one trading (an exchange rate of 3:1), which requires three RGGI allowances for each ton emitted in California and only one-third of a California allowance for each ton emitted in RGGI. The California allowance price is roughly double the RGGI allowance price in autarky, so these two scenarios span a range of exchange rates that are both below and above the ratio of prices under autarky. An allowance exchange rate can mediate the differences in marginal cost. However, as anticipated in section 2, the emissions outcome is not determined by the sum of the emissions caps in this context because an emissions allowance that is transferred between jurisdictions confers a license to emit different amounts in the two jurisdictions. In addition, although we do not explore this in the model, we expect the outcome also to be affected by the presence of companion policies that directly support technologies such as renewables or energy efficiency. The effect of these policies on the flow of allowance value between jurisdictions could introduce a strategic dimension to the policy architecture.

With one-for-one trading of allowances between the two programs, higher California allowance prices suggest that allowances would flow from RGGI to California.[29] The result would cause allowance prices to rise in RGGI and fall in California. As allowance prices in RGGI rise as a result of linking, emissions in RGGI would be expected to exhibit a greater response than in California because the supply of emissions reductions is more elastic in RGGI than it is in California, as illustrated in Figure 3. The extent to which the equilibrium allowance price in California can fall as a result of imports from RGGI is constrained by the California price floor.[30] Linking the programs with one-for-one trading imposes the California price floor on both, as described in Results 1 and 2 markets. As a result, allowance prices in RGGI rise by nearly 80 percent, while allowance prices in California fall by only about 10 percent before they reach the floor.

**Figure 3. Marginal Abatement Cost Curves and Results under One-for-One Trading**




One-for-one linking has three other important effects:

[29] One-for-one trading actually would involve a conversion factor as the programs are currently organized because a California allowance is denominated in metric tons and a RGGI allowance is denominated in short tons. One-for-one trading corresponds to equivalent tons.

[30] If RGGI supplied enough allowances to satisfy demand in both markets, the price would fall below the California price floor, but otherwise the market price of allowances in RGGI will be bid up to the California floor as we find in our modeling.

- *Emissions*. Linking shifts the location of $CO_2$ emissions from RGGI to California. Emissions from generators covered by the California program rise by 5 percent, while emissions in RGGI fall by 23 percent compared with emissions when unlinked. As a result of the price floor being spread across the two programs, total emissions from the two programs combined are lower than when they are not linked; combined emissions in the two regions are 26 percent below baseline levels with one-for-one linking, compared with 17 percent below baseline when the programs operate separately.
- *Retail electricity prices*. Linking of the two programs has virtually no effect on electricity price in California because of the allocation of allowance revenues to local distribution companies.[31] The average electricity price in RGGI is roughly 1 percent higher as a result of linking. In RGGI, most of the allowance revenues go to energy efficiency programs, which reduce electricity demand and price.[32]
- *Potential leakage*. As a result of the higher allowance prices in RGGI due to linking, power imports into the region increase by roughly 15 percent (the increase is equivalent to 5 percent of total consumption), suggesting that linking at one-for-one may contribute to emissions leakage in the RGGI region. Incentives for leakage in California would presumably be reduced because emissions prices fall with linking.

A comparison of total costs across scenarios in the model is not straightforward because the model has a detailed representation of regulatory structure. RGGI is modeled as a competitive power market. However, California resembles a cost-of-service territory with average cost pricing in the model, so changes in electricity price can have unintuitive outcomes on the cost measure (e.g., welfare can increase when electricity prices rise). Consequently, we focus on the distribution of costs within each system.

The distributional effects of linking clearly differ across geography and constituencies as displayed in Table 1. The effects of linking are reported in dollars per megawatt-hour (MWh), with positive values representing net benefits and negative values representing net costs, and are

[31] We assume this revenue is used to offset changes in electricity price. In practice, the majority of revenue associated with the auction of allowances to the electricity sector is returned as per customer account dividends received biannually, so customers see prices rise for five months before seeing a credit in the sixth month, thereby mostly preserving the perception that electricity prices are higher due to the program.

[32] The Haiku model has endogenous representation of the reduction in demand resulting from investments in energy efficiency. We adopt conservative assumptions about the effectiveness of those expenditures in reducing demand.

disaggregated into the effects on allowance value, resource cost, and electricity price. Table 1 shows that one-for-one trading leads to a small electricity price increase in RGGI, which hurts consumers. Because allowance prices rise in RGGI, the government collects more revenue from the allowance auction. This revenue is used to pay for energy efficiency and thus contributes to the low impact on electricity price. Fossil generators in RGGI benefit from the higher electricity price, but this benefit is outweighed by the combination of higher allowance costs and higher operating costs.[33,34]

In California, one-for-one trading has net positive effects for both consumers and fossil generators. Lower wholesale electricity prices affect consumers positively, but much of that effect is wiped out by the lower allowance revenues going to local distribution companies. Fossil producers are hurt by the lower electricity prices, but reductions in allowance costs and overall resource costs more than compensate. As described in Result 4, linking has opposite distributional effects in each jurisdiction.

[33] Resource cost/flow for fossil generators is the cost category that most closely matches the cost function of the analytic model, $C(Q,E)$.

[34] Note that the net effect indicated in the table is not strictly additive across interest groups, because the use of revenues to the government influences the outcome for consumers and generators.

**Table 1. Incidence of Benefits and Costs of One-for-One Trading**

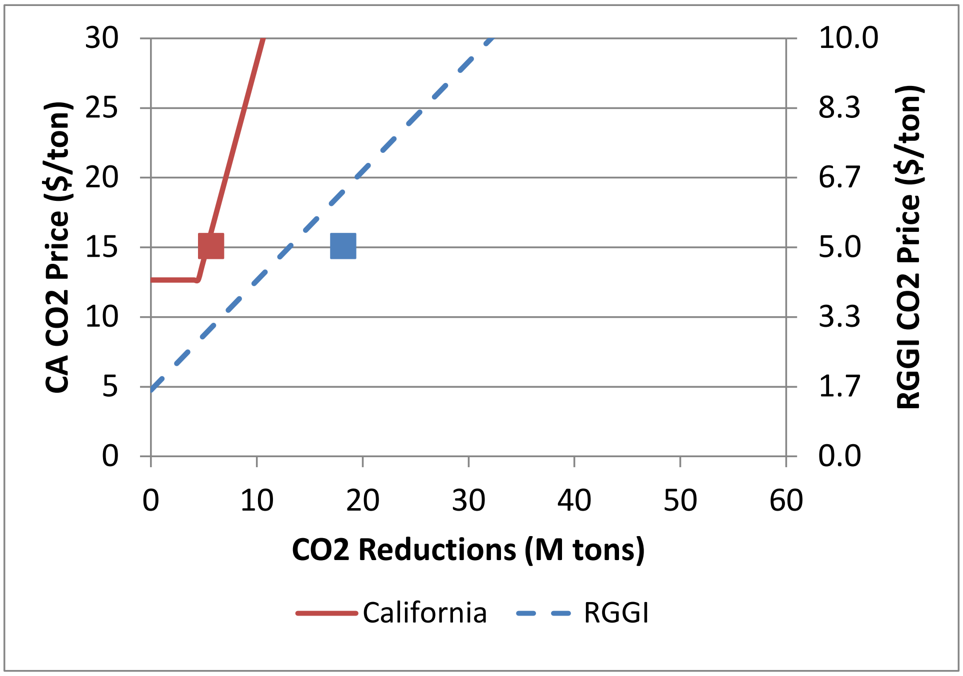
| *$/MWh* | RGGI | | | California | | |
|---|---|---|---|---|---|---|
| | Consumers | Government | Fossil Generators | Consumers | Government | Fossil Generators |
| Allowance Value | | 1.4 | -2.8 | -1.1 | | 0.6 |
| Resource Cost/Flow | | | -6.9 | | | 3.8 |
| Electricity Price | -1.0 | | 1.0 | 1.2 | | -1.2 |
| **Net Effect** | **-1.0** | **1.4** | **-8.6** | **0.1** | **n/a** | **3.2** |

### *Results for Three-for-One Trading*

Three-for-one trading provides a rough adjustment for the relative stringencies of the two programs but reduces the opportunities for costs savings from shifting $CO_2$ emissions from RGGI to California because of the requirement that three RGGI allowances be surrendered for every ton of emissions from sources regulated under the California program. Conversely, regulated sources in RGGI require only one-third of a California allowance to cover one ton of emissions in RGGI. The trading ratio also means that the effective minimum price in RGGI is by construction one-third of the price floor in California. This trading ratio lowers demand for RGGI allowances in California and increases demand for California allowances in RGGI, compared to one-for-one linking. Figure 4 shows the resulting allowance prices and emissions reductions from three-for-one trading. Note that the RGGI allowance price is read off the right-hand axis, which is one-third of the California allowance price on the left-hand axis. The box point is away from the line because it indicates the outcome from the specific modeling scenario and the line is the linear prediction over this range. The resulting allowance price in RGGI of $5/*ton* is between the exchange-adjusted prices in autarky, where the price for compliance in RGGI using a RGGI allowance is $7.2/*ton* and the exchange-adjusted price using a California allowance is $4.73/*ton*.[35]

[35] Similarly, the resulting allowance price in California of $15/*ton* is between the exchange-adjusted prices in autarky, where the price for compliance in California using a California allowance is $14.2/*ton* and the exchange-adjusted price of using a RGGI allowance is $21.6/*ton*.

**Figure 4. Marginal Abatement Cost Curves and Results of Three-for-One Trading**




Linking at three-for-one compared with an unlinked regime has several other consequences:

- *Emissions*. This program leads to a 6 percent increase in emissions in RGGI relative to the unlinked case and only a small change in emissions in California. As a result, total emissions of $CO_2$ in the two regions increase to 14 percent below baseline levels, compared with 17 percent below baseline levels when the programs are unlinked.
- *Retail electricity prices*. With three-for-one trading, linking has only a small effect on retail electricity price in California, but the average retail electricity price in RGGI increases by about 1 percent relative to the unlinked program.
- *Potential leakage*. Power imports into RGGI fall and total generation in RGGI rises as a result of the reduction in allowance cost associated with producing power in the region, suggesting leakage is less of a concern in RGGI under three-for-one trading.

With three-for-one trading, the benefits of linking in the RGGI region accrue primarily to fossil generators, which face lower allowance and resource costs. Consumers in the region also see slight benefits from lower electricity prices, while government revenues from allowance sales are lower because of lower allowance prices in RGGI. In California, fossil generators are negatively affected by the higher allowance costs and the lower electricity price. For consumers, higher allowance value results in a direct benefit in the form of allowance revenue rebates, which complement the reduction in wholesale electricity costs relative to the unlinked scenario. Although electricity prices would be expected to increase with an increase in allowance prices, the assignment of allowance value to local distribution companies and the dynamic nature of capacity investments and electricity consumption in Haiku result in lower electricity prices in California under this scenario.

**Table 2. Incidence of Benefits and Costs of Three-for-One Trading**

| *$/MWh* | RGGI | | | California | | |
|---|---|---|---|---|---|---|
| | Consumers | Government | Fossil Generators | Consumers | Government | Fossil Generators |
| Allowance Value | | -0.5 | 1.2 | 0.3 | | -0.4 |
| Resource Cost/Flow | | | 1.2 | | | 0.5 |
| Electricity Price | 0.2 | | -0.2 | 0.5 | | -0.5 |
| **Net Effect** | **0.2** | **-0.5** | **2.2** | **0.7** | | **-0.4** |

## 5. Conclusion

This paper provides a framework for analysis of the linking of emissions trading systems. We develop an analytical framework for linking of programs with different features, including stringency, as measured by allowance prices, and a cost containment mechanism. We then apply that framework to the potential linking of the California and RGGI $CO_2$ emissions allowance markets. In a qualitative evaluation, we conclude these markets are almost ready for linking when evaluated based on administrative measures and the expected functioning of a common market. We then simulate the linking of these programs using a model of the US electricity sector; we analyze the programs in a stylized way, incorporating only the electricity sector portion of the now economy-wide cap-and-trade program in California. Despite the near readiness for linking, our simulation exercise suggests the difference in stringency and the different program designs introduce potentially difficult outcomes under linked market scenarios, some of which are predicted by our analytical model and others that are unexpected.

Our analytical and simulation models demonstrate that formal linking of emissions trading systems 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. One reason this uncertainty could result is the presence of cost 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. The use of an exchange rate to reconcile differences in stringency between the programs also could have the effect of changing aggregate 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. 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 also has important implications for the economic costs of the trading systems. Our analytical model finds that one-for-one linking improves the cost-effectiveness of emissions reductions, although the use of an exchange rate undoes some of these cost reductions and may even yield a linked system that is costlier that the combination of the independent systems. Additionally, a variety of subtle distributional effects emerge even when aggregate emissions are equal to the sum of the two independent caps, but which might be exacerbated when total emissions change. We consider the effects on three constituencies – consumers, producers and government. We find that whenever linking occurs, at least one of these groups suffers negative effects. Increasing attention is also being given to the distribution of emissions reductions that result from carbon trading programs, despite the global nature of climate change. This attention is focused on the concern that not all communities see reductions in conventional 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. 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.

The path forward for linking would appear significantly easier if programs initially have comparable stringency before linking is pursued – a criterion that is mandated but somewhat imperfectly defined by California state law under Senate Bill 1018. When comparable stringency is in place, then the expanded carbon market offers economic benefits as well as resilience to external factors, such as changes in weather or economic activity. In the meantime, until formal linking is achieved, incremental alignment of institutions, program design, and stringency represents an important but informal linking by degrees that points toward eventual broad-based carbon policy.

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## Appendix

### *Modeling California and RGGI*

The modeling analysis of linking involves comparing the results of linked programs with those from unlinked programs. The first step in modeling the effects of linking is to specify the requirements imposed by the two trading systems on electricity generators within each region. In the case of California, the program extends beyond the state border, as those who deliver power to the California market that is generated outside the state also must surrender allowances to cover the associated $CO_2$ emissions. Throughout this modeling analysis, the central case assumptions regarding fuel prices and underlying electricity demand growth projections are based on now outdated assumptions in the US Energy Information Administration's (EIA) 2011 Annual Energy Outlook.[36] However, the main results are robust to different underlying parameters.

The Haiku model solves for selected simulation years through 2035. In this analysis, we select 2015, 2017, and 2020 as the primary simulation years covering the time period for California's cap-and-trade program. The phase-in of emissions caps in California is coincident with a dramatic ramp up in the requirements of the renewable portfolio standard and thus the rapid introduction of renewables, which has important implications for allowance flows between California and RGGI. To capture these effects, we focus on 2020.

We model an emissions cap in California's electricity sector in order to achieve allowance prices roughly comparable with those anticipated by futures prices in the summer of 2012, about $18 per short ton in 2020 (in 2009 dollars). We use the resulting cumulative emissions across all years at these prices to create a trajectory of cap levels that decrease linearly each year, and we solve the model over the entire horizon through 2035. We assume that the emissions levels must not exceed the cap in each year, meaning no banking of allowances for future use occurs. The price floor in California rises at 5 percent per year in real terms, reflecting the program design. There is no explicit offset market or description of companion (technology) policies other than the renewable portfolio standard, but the electricity sector contribution to the cap is calculated taking these policies into account.

We include emissions associated with electricity imports into California under the cap to reflect regulators' intent to control emissions leakage. We assume that no contract shuffling in the imported power market will take place in response to the requirement to surrender allowances on

[36] For more information on those assumptions, see the description of the baseline scenario in (Burtraw et al. 2012).

imported power. In our model, the decision at the margin about whether to import power uses the marginal emissions rate for each neighboring region that exports power to California. The volume of allowances required for imported power is based on the average emissions rate for each neighboring region.

We model the RGGI cap by simulating a $6 per short ton allowance price (in 2009 dollars) on $CO_2$ emissions in 2015 that rises at 5 percent per year in real terms.[37] We use the resulting cumulative emissions across all years at these prices to create a trajectory of cap levels, which start at baseline levels at the beginning of the time horizon and decrease linearly each year. We assume that the cap is binding (emissions levels will hit the cap) and that no banking of allowances for future use occurs.

[37] We assume the price floor is unchanged.