VU Research Portal

Trade between mass- and rate-based regulatory regimes

Fischer, Carolyn; Mao, Biao; Shawhan, Daniel

published in

Energy Economics
2018

DOI (link to publisher)

[10.1016/j.eneco.2018.04.031](https://doi.org/10.1016/j.eneco.2018.04.031)

document version

Publisher's PDF, also known as Version of record

document license

Article 25fa Dutch Copyright Act

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Fischer, C., Mao, B., & Shawhan, D. (2018). Trade between mass- and rate-based regulatory regimes: Bad for emissions? *Energy Economics*, 73, 326-336. <https://doi.org/10.1016/j.eneco.2018.04.031>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Trade between mass- and rate-based regulatory regimes: Bad for emissions?

Carolyn Fischer^{a,b,c,d}, Biao Mao^e, Daniel Shawhan^{a,f,*}

^a Resources for the Future, 1616 P St. NW, Washington, DC 20036, USA

^b Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081, HV, Amsterdam, Netherlands

^c Gothenburg University, 405 30 Gothenburg, Sweden

^d CESifo Research Network, Munich, Germany

^e Department of Economics, Rensselaer Polytechnic Institute, 110 8th St, Troy, NY 12180, USA

^f Dyson School of Applied Economics and Management, Warren Hall, Cornell University, Ithaca, NY 14853, USA

ARTICLE INFO

Article history:

Received 31 October 2017

Received in revised form 15 February 2018

Accepted 18 April 2018

Available online 26 April 2018

JEL classification:

Q48

Q41

Q42

Q53

Q54

Q58

Keywords:

Cap and trade

Carbon price

Performance standard

Linking

Leakage

Electric power

ABSTRACT

If one jurisdiction regulates power plant emissions with a cap-and-trade (mass) program and another with an intensity (rate) standard, is it a good idea for them to link? Specifically, what effects does introducing electricity and rate-mass allowance trade between differently-regulated regions have on emissions and ultimately welfare? We explore these questions first with a simple theoretical model and then with a sophisticated numerical model of the electricity sector. The theoretical model isolates the policy effects by assuming that two otherwise identical regions are regulated differently. With fixed demand, their autarky marginal abatement costs are identical, but electricity prices are lower in the rate-limited region. Adding electricity trade shifts generation to the rate-limited region, expanding its allowance allocation, while emissions remain capped in the mass-capped region. Adding rate-mass allowance trade exacerbates this shift in generation and expansion of emissions. The increase of emission damage could make the net welfare effects negative. However, if the mass cap is sufficiently more stringent than the rate limit, allowing rate-mass allowance trade in the presence of electricity trade can lower emissions. The numerical model of the eastern US illustrates the effects predicted in the theoretical model, and projects their magnitudes. In our simulation that is loosely based on the US Clean Power Plan, the estimated CO₂ damage makes the estimated net benefits of allowing rate-mass trading negative. Our results also illustrate that linking can shift the geographic distribution of SO₂ and NO_x emissions, which can counteract the effect of the CO₂ damage on estimated total welfare.

© 2018 Published by Elsevier B.V.

1. Introduction

Carbon trading regimes are highly heterogeneous. Some establish overall emission targets—*mass caps*—and allocate the allowances, while others set emission intensity or performance standards—*rate limits*. These two basic types or regimes might come to coexist in the same country or region (e.g. within China, Canada, the US, or part of any multi-country continent). For example, the Clean Power Plan proposed in the United States by the Obama Administration envisioned allowing each state in the US to choose whether to adopt a mass cap or a rate limit. The prospect of such a situation raises questions about linking to create a broader trading program.

This paper focuses on the question of linking rate-based and mass-based regulatory programs by increasing the transmission capacity between them or by allowing emission allowance trading between them

(rate-mass trading). A large US electric utility company, Southern Company, developed a plan for rate-mass trading and proposed it to the US Environmental Protection Agency (USEPA) that it be allowed under the Clean Power Plan (Southern Company 2016).¹ In another context, the government of Alberta, which has an emissions intensity target, is exploring options for linking with provinces that have mass-based emissions trading schemes, namely Quebec and Ontario (Viaciulis 2017).

The results of the modeling in this paper suggest that allowing rate-mass trading is likely to increase overall carbon emissions unless the mass program is much more stringent than the rate program, and that

¹ This paper elaborates on a rulemaking comment submitted to the US Environmental Protection Agency (Burtraw et al. 2014) about the proposed Clean Power Plan. Subsequent to the feedback process, USEPA proposed to allow trading only within like-structured regimes, with the exception that renewable energy in a mass-capped state could be used for compliance in a rate-limited state. (For a simple overview, see <http://www.synapse-energy.com/about-us/blog/tricks-trade-who-can-sell-emissions-credits-whom-clean-power-plan-part-1-2>.) However, there remained interest on the part of certain industry members to be allowed flexibility to trade across states with different regimes.

* Corresponding author at: Resources for the Future, 1616 P St. NW, Washington, DC 20036, USA.

E-mail address: DLS77@cornell.edu (D. Shawhan).

adding transmission capacity between the regions is likely to increase overall carbon emissions unless the mass program is much less stringent than the rate program. These potential outcomes seem at odds with the overall objective of emissions reduction policies and therefore deserve careful consideration.

Emission rate limits effectively subsidize generation at the same time that they price emissions (Fischer 2001). The reason is that, under a rate limit, unlike under a mass cap, generating more earns a firm emission allowances. Cap-and-trade programs that either auction allowances or give them away based on variables that predate the program do not generally subsidize generation. If energy demand were perfectly inelastic, the subsidy resulting from a rate limit would not be distorting in the absence of trade (Fischer and Fox 2007; Fell et al. 2015), nor would it be distorting among like-regulated states, provided the merit order were not affected (Bushnell et al. 2017). If, however, energy consumption is responsive to prices, subsidizing generation encourages more production, lower electricity prices, and less demand-side conservation. Thus, to meet the same emissions target, a performance standard would need to seek a more stringent emissions rate reduction than would be required under an emissions cap (Fischer and Fox 2007; Fischer 2003). Furthermore, the distortion to conservation behavior is difficult to undo: while credits for energy efficiency can counterbalance the effect of the subsidy on investments in energy efficiency improvements, the incentive to overuse energy services remains (Fell et al. 2015).² Empirical studies also confirm that states in the US Nitrogen Oxide Budget Program that chose an updating allocation (granting allowances based on generation, as with rate-based regulation) did increase their electricity production relative to plants in states that chose a fixed allocation (Lange and Maniloff 2017).

The anticipated rise in overall emissions originates from the nature of linkage and the design of rate-based programs. Fischer (2003) discusses such linking for programs covering sectors that are imperfect substitutes (e.g., energy-intensive manufacturing in different jurisdictions). Linking rate-based and mass-based programs creates gains from trade for both programs, as differences in abatement costs between the two markets dissipate and their allowance prices align. In a binding mass-based program, these gains from trade do not affect emissions because, by definition, allowance quantities remain static. In a rate-based program, however, Fischer (2003) argues that gains from trade always act to depress product prices in the rate-limited sector, which in turn tends to increase consumption and hence production.³ The increase in production in the emissions rate-limited region or sector leads to the issuance of a higher number of allowances, given that rate-based programs issue a variable supply of allowances depending on the firms' volume of goods production. She identifies some possible exceptions, however, such as when the goods produced in the two sectors are close substitutes and trading lowers the emissions price for the mass-capped sector sufficiently to make the mass-capped sector product relatively more competitive, thus displacing output in the rate-limited sector.⁴

The case of electricity is qualitatively different from that envisioned in Fischer (2003). The goods produced (kWh) are either perfect substitutes from a demand perspective and thus easily traded, as is the case for generators feeding the same grid, or essentially they are not traded, as is the case for generators serving different, unconnected grids or when trade is sufficiently limited by transmission constraints. Furthermore, the market and abatement costs are arguably different; within

the electricity sector of a region, there are multiple sources with different generation costs and different emissions rates, and much emissions reduction occurs through switching among fuel sources.

Bushnell, Holland, Hughes, and Knittel (2017) (henceforth BHHK) use a merit-order model to compare mass- and rate-based regulatory systems and the strategic incentives of states to choose them when electricity is traded freely. They show that rate-based and mixed regulations each may still induce efficient supply if the optimal merit order is obtained. When states are heterogeneous, trade in emissions credits lowers costs; for trade among rate-limited states, the result may be to raise or lower emissions. Their simulations of the Western electricity system with a single, common emission rate standard and emissions allowance trade have higher emissions than systems with individual standards and no such trade; however, they do not explore credit trading across mass- and rate-limited groups numerically. Other numerical studies, including Niemeyer (2016), find that credit trading among states with individual rate-based standards lowers internal (i.e. private) costs but increases emissions relative to no trade.

In contrast to previous studies, we parse the twin roles that electricity trading and emission allowance trading play in the effects of mixed regulations, particularly over the longer term.⁵ First, a simple theoretical model builds intuition by isolating the effects of regulatory differences in two otherwise identical regions. It shows that, even without interregional allowance trade, electricity trade between differently regulated regions raises total emissions relative to no trade. Enabling electricity trade allows production to shift generation to sources in the region with the rate limit, which forgives the costs of average embodied emissions. With less generation and more imports in the mass-capped region, local emissions would fall below the cap if the allowance price remained the same. As a consequence, the allowance price falls in that region. This causes the mass region to shift away from clean generation. Total emissions remain the same in the mass region, but electricity production there is smaller and more emission intensive. Meanwhile, expanded production in the rate region necessarily means total allowance allocations and therefore emissions rise. Allowing allowance trade between the mass-capped and rate-limited regions further exacerbates this shift in production and rise in emissions.

Simulations with a sophisticated numerical model introduce more nuance to the results, underscoring the importance of the direction of trade without additional transmission capacity or the ability to have inter-regional ("rate-mass") allowance trading in determining the effects of those two flexibility mechanisms. A scenario in which the mass region's emissions are capped at 70% of business-as-usual emissions and the rate region's emission rate is limited to 70% of its business-as-usual emission rate affirms results of the theoretical model, as both electricity trade and allowance trade between the two regions raise emissions. However, as hypothesized in the theory section of this article, rate-mass allowance trade can lower emissions if it raises emissions prices in the rate-limited region, which requires a much stricter target in the mass-capped region than in the rate-limited region. Increased electricity trade capacity can lower emissions if it results in greater exports from the mass-capped region to the rate-limited regime, which requires a much looser target in the mass-capped region.

The numerical model also estimates damage from sulfur dioxide (SO₂) and nitrogen oxide (NO_x) emissions, and estimates total social surplus. It finds that, with the 70% emission limits and with the assumed mass and rate regions, both added transmission and rate-mass allowance trading decrease estimated total social surplus.

² The analysis by Fell et al. (2015) thus reveals two special cases where rate-based regulation within a jurisdiction may be efficient: 1) if demand for energy is perfectly inelastic, and 2) when demand for energy services is perfectly inelastic, in which case the inefficiency of the subsidy to generation may be offset by a subsidy to energy efficiency.

³ Consumption always rises if demand is independent and price responsive; otherwise the net effect can also depend on the price change for the other sector's good.

⁴ We will use "mass-capped" or "rate-limited" to describe sectors or regions under mass-based or rate-based regulations, respectively.

⁵ In a particular program that applies an emissions rate limit, the tradable emissions right may not be called an "allowance" and may not be denominated in terms of CO₂ mass. However, such a program can usually still be represented as one in which the tradable emissions rights are allowances denominated in tons of CO₂. Holland et al. (2009) analyze this point in some detail.

2. Simple theoretical model

To isolate the effects of cross-scheme trading, consider first a simple case of two symmetric regions with identical costs and fixed demand. This case is interesting because previous studies ignoring trade find no distortions from rate-limited emission regulation policies when electricity demand is perfectly inelastic (e.g., Fell et al. 2015).⁶

Two forms of generation are available, a relatively dirty source (say, coal) and a relatively clean source (say, natural gas combined cycle or renewables). We assume each has an upward sloping supply curve, reflecting increasing marginal costs of supply in the medium to long run when capacities can be adjusted (e.g., as more productive sites become scarce, or as pressure on demand for scarce fuel inputs increases).⁷

In the absence of emissions regulation, the two regions would, by the symmetry assumption, have identical generator dispatch, identical costs, and identical emissions; and the ability to trade electricity between them would not matter.

Let us then impose different regulations: a carbon dioxide (CO₂) emissions mass cap-and-trade program in region *M*, set at share *x* of baseline emissions, and a tradable CO₂ emissions rate-based (performance) standard in region *R*, set at share *x* of the baseline emissions rate. Under the rate-based regulation, firms earn emissions allowances in proportion to the number of megawatt-hours they generate. If their emissions are greater than the number of allowances they earn, they must buy more from firms that have extras. If their emissions are less than the number of allowances they earn, they can sell the extras. Without electricity trade or rate-mass allowance trade being possible, and given the fixed demand, each region would produce the same outcome under the different regulations. Thus, we have eliminated any baseline inefficiencies (since demand is fixed, avoiding the conservation failure of the rate-based standard) as well as any gains from trade that would result from cost heterogeneities. Now let us see what happens when these two regions—whose only difference is the type of regulation—can trade electricity, and then what happens when they can trade both electricity and allowances.

Formally, let *D* be electricity demand in each region. Let *q_{is}* be the quantity of generation in region *s* of type *i*, for *i* = {*d*, *c*} dirty and clean technologies. The cost of generating *q_{is}* is *C_i(q_{is})* = *f_i* + *a_iq_{is}* + *b_i(q_{is})²/2*, where the clean technology is assumed to have a higher marginal cost intercept: *a_c* > *a_d*. Emissions rates are *u_d* > *u_c*, leading to emissions for region *s* of *E_s* = *u_dq_{ds}* + *u_cq_{cs}*; emissions prices are *t_s*.

The equilibrium price of electricity, *p_s*, is a result of the supply and demand equilibrium. If the two regions do not trade electricity with each other, that requires *q_{ds}* + *q_{cs}* = *D* for *s* = {*M*, *R*}; with electricity trade, the equilibrium constraint is *q_{dM}* + *q_{cM}* + *q_{dR}* + *q_{cR}* = 2*D*. Generators maximize profits net of tax payments and allocations. With fixed demand, maximizing total surplus is equivalent to minimizing generation costs.

2.1. Firm incentives

2.1.1. Mass-capped sector

In the mass-capped sector, emissions are constrained to be below a fixed allocation, *A*. For simplicity we assume this allocation is

grandfathered to the electricity suppliers. The representative price-taking generator uses technologies of each type *i* = {*c*, *d*} and maximizes

$$\pi_M = \sum_i \{(p_M - t_M u_i) q_{iM} - C_i(q_{iM})\} + t_M A$$

The first-order conditions for generation from type *i* imply.

$$p_M = t_M u_i + a_i + b_i q_{iM} \quad (1)$$

In equilibrium, *t_M* is the shadow value of the constraint

$$u_d q_{dM} + u_c q_{cM} = A. \quad (2)$$

2.1.2. Rate-based sector

In the sector subject to the performance standard, *r*, the representative price-taking generator maximizes.

$$\pi_R = \sum_i \{(p_R - t_R(u_i - r)) q_{iR} - C_i(q_{iR})\}$$

The first-order conditions imply

$$p_R = t_R(u_i - r) + a_i + b_i q_{iR} \quad (3)$$

In equilibrium, *t_R* is the shadow value of the constraint

$$u_d q_{dR} + u_c q_{cR} = r(q_{dR} + q_{cR}) \quad (4)$$

and *p_R* ensures *q_{dR}* + *q_{cR}* = *D*.

2.1.3. Flexibility

Flexibility mechanisms allow permits to be traded across regions. In this case, allowance prices are equalized, so *t_M* = *t_R* = *t^{flex}*, and total emissions must equal total allocations:

$$u_d q_{dM} + u_c q_{cM} + u_d q_{dR} + u_c q_{cR} = r(q_{dR} + q_{cR}) + A \quad (5)$$

2.2. No emissions regulation

In the absence of emissions regulation, *t_M* = *t_R* = 0. Firms in both regions have the same first-order conditions, and face identical demand, so the ability to trade electricity does not change the outcome. In both cases, *p_s* ensures *q_{ds}* + *q_{cs}* = *D*. We use this equilibrium as our baseline.

$$q_{ds}^0 = q_d^0 \equiv \frac{b_c D - a_d - a_c}{b_c + b_d}; \quad q_{cs}^0 = q_c^0 \equiv \frac{b_d D - a_d - a_c}{b_c + b_d}$$

$$E_s^0 = E^0 \equiv \frac{(u_d b_c + u_c b_d) D - (u_c + u_d)(a_d + a_c)}{b_c + b_d}$$

⁶ As noted in the introduction, Fell et al. (2015) distinguish between this case and that of fixed demand for energy services.

⁷ These supply curves can be considered a smoothed representation of a merit order of multiple sources using the same fuels but with different ages and costs, or more generally a medium-run characterization of the market; see, e.g., Fischer and Newell (2008). This representation contrasts with that of the BHHK merit-order model in which supply capacities are fixed and marginal costs are constant for the given technologies, which is more consistent with short-term analysis. In their context, policies that may be distorting in the long run can achieve supply efficiency in the short run, if they lead to the proper merit order.

Fig. 1 depicts the basic model, where demand in each region is like a bathtub of fixed size and can be filled by a mix of dirty and clean generation, with each region as a mirror-image of the other. The dirty and clean supply curves are shown for each region, along with the price of electricity at the cost-minimizing mix of dirty and clean generation. In the absence of emissions regulation policy, the outcomes are identical, whether electricity trade exists or not.

Fig. 1. Identical regions with no emissions regulation policy.

2.3. Emissions regulation

Differing regulatory stringency can matter, but to concentrate on the mechanism design, we assume identical percentage reduction goals for each scheme. Thus,

$$A = (1-x)E^0$$

$$r = (1-x)E^0/D$$

2.3.1. No electricity trade

If electricity trade and allowance trade are not possible, each region meets its own demand, subject to the respective emissions constraint. In the case of the mass cap, these combined constraints imply $q_{dM} = (A - u_c D)/(u_d - u_c)$; with the rate-based regulation, they require $q_{dR} = (r - u_c)D/(u_d - u_c)$. Since $A = rD$, the allocative outcomes are identical, with $q_{iM} = q_{iR}$, and $E_M = E_R = (1-x)E^0$. Furthermore, from (1) and (3) we see that the difference in marginal costs between the dirty and clean sources is $t_s(u_d - u_c)$ for both the mass cap and the rate-based standard, implying identical allowance prices in the no-trade equilibrium: $t_M = t_R$. With marginal cost pricing, however, the output subsidy associated with rate-based regulation does imply that $p_R < p_M$, seen by comparing (1) and (3): the value of the allocation is transferred to the consumers with rate-based regulation.

Fig. 2 depicts the outcome of different regulations on our otherwise identical regions without trade, taking the example of a non-emitting clean generation source. The regulatory targets effectively require the two regions to have the same mix of generation—i.e., the same amount of dirty energy—and thus the same cost differential between the dirty and clean sources. In the mass-capped region, that differential is created by an implicit tax on dirty generation that is fully passed on to consumers, whereas in the rate-limited region, the policy effectively combines a smaller net tax on dirty generation with a net subsidy for clean generation, resulting in a lower retail electricity price.

In this example of identical regions and targets, since the resulting emissions prices are identical, allowing flexibility only to trade allowances across regions does not affect the outcome at all. Somewhat more generally, we can state the following proposition:

Proposition 1. *Without electricity trade, allowance emission allowance trading across differently regulated regions with fixed demand has no effect on emissions.*

Proof. With fixed demand and no electricity trade, total allowance allocations (and thereby emissions) are fixed at $A + rD$; regardless of the A and r and resulting autarky allowance prices, which may diverge, total emissions are fixed. Therefore, trade in allowances across differently regulated regions primarily affects the distribution of emissions and surplus across producers and consumers.

Fig. 2. Identical, differently regulated regions with no trade. Region R's limit on average emission rate per MWh raises the cost of dirty generation but also subsidizes all generation, lowering the electricity price relative to that in Rate M. Note: Price P_R corresponds to the height of the intersection of the dashed Region-R supply and demand curves.

Again, this hinges on the assumption of fixed demand. (The case of price-responsive demand has been explored before and reveals that demand responses would allow the rate-limited region to expand emissions; see Fischer 2003.) In this manner we isolate the interaction between heterogeneous regulations and electricity trade. Next, we see that electricity trade in effect leads to elastic demand for each region's suppliers.

2.3.2. Electricity trade

Now, suppose electricity is traded across regions, but allowance trade across the regions is not allowed. With electricity trade, the regulatory equilibrium changes. Recall that equalization of all the first-order conditions in a common electricity market with a single output price requires.

$$p^{Trade} = t_M^{Trade} u_i + a_i + b_i q_{iM} = t_R^{Trade} (u_i - r) + a_i + b_i q_{iR}.$$

The new equilibrium price must lie between the autarky prices with different regulations: $p_M^{NoTrade} > p^{Trade} > p_R^{NoTrade}$. Price equalization implies that $q_{iR} - q_{iM} = ((r - u_i)t_R^{Trade} + u_i t_M^{Trade})/b_i$. Clearly, more clean generation will be provided in the rate-limited region than in the mass-capped region (since $r > u_c$), while the redistribution of dirty generation is less clear. However, the total amount of emissions increases, as explained in the following proposition.

Proposition 2. *Electricity trading across differently regulated (but otherwise identical) regions increases emissions and lowers the emissions price in the mass-capped region.*

Proof. Since $p^{Trade} > p_R^{NoTrade}$, total production in the rate-limited region expands, and since allowance allocation in that region is proportional to output, total emissions expand. Since $p^{Trade} < p_M^{NoTrade}$, total generation in the mass-capped region falls. But generation by the two sources cannot decline proportionately, or emissions would fall below cap. Rather, clean generation must decline disproportionately, while dirty generation actually expands to meet any shortfall in emissions.⁸ This allocation of production requires a smaller marginal cost gap between the two sources, meaning the emissions allowance price in the mass-capped region must fall. We solve the equilibrium mathematically in the Appendix A.

Thus, even though the generation outcomes were identical without trade, with electricity trade, asymmetric regulation causes the generation mixes to change. More clean generation occurs in the rate-limited region. Trade allows the rate-regulated generators to exploit their

⁸ See also Böhringer and Rosendahl (2010).

marginal cost advantage and expand into the mass-capped region's electricity market, crowding out local generation. This effect will be tempered to the extent that the emissions price falls in the mass-capped market as a consequence.

Consider the case of a non-emitting clean energy source, as in the first two Figures. In such a case, the emissions cap in M fixes the amount of dirty generation in that region. When electricity trade harmonizes the electricity prices, production shifts from M to R because the rate regulation effectively subsidizes generation, driving up rate-region electricity price p_R and pushing down p_M until they are equalized. Because the amount of dirty generation in the mass-capped region is fixed, the allowance price t_M falls, and only clean generation is crowded out. In other words, generation in the mass-capped region gets smaller and more emission intensive. By contrast, the rate region's additional generation is a proportional mix of clean and dirty, according to the intensity standard, such that as total generation expands in that region, emissions expand proportionately.

2.3.3. Full flexibility

Now, in addition to electricity trade between the regions, suppose that emission allowances too can be traded between the regions. In this case, the equalization of all the first-order conditions in a common market requires,

$$p^{Flex} = t^{Flex} u_i + a_i + b_i q_{iM} = t^{Flex} (u_i - r) + a_i + b_i q_{iR}$$

which implies that $q_{iR} - q_{iM} = rt^{Flex}/b_i$. That is, with emission and electricity prices harmonized, the rate-limited region generates unambiguously more electricity from both kinds of sources than does the mass-capped region, due to the subsidy from the rate-based allocation.

Proposition 3. *Full flexibility (electricity and rate-mass allowance trading together) across differently regulated (but otherwise identical) regions results in higher emissions and a lower emissions price than with neither kind of trading.*

Proof. With more generation in the rate-regulated region than without trade, total allowance allocations and emissions must also be higher. With more allowances available for the same total amount of generation, the emissions constraint is loosened, meaning the allowance price with full flexibility must be lower than the no-trade allowance price.

We have just shown that emissions are higher with both electricity and allowance trade than with neither kind of trade. We can also show that emissions are higher with both kinds of trade than with electricity trade alone:

Proposition 4. *Allowance trading between differently regulated (but otherwise identical) regions exacerbates the increase in emissions from electricity trading between the two regions.*

Proof. In the Appendix A, we demonstrate that the effect on emissions of adding allowance trading carries the same sign as the effect of electricity trade, which is to raise emissions.

The explanation begins with the observation that additional gains from trade in allowances further lower costs and allow more shifting of production to the rate-regulated region. The mass-capped region, its allowance prices depressed after being out-competed under electricity trade by rate-regulated generators, can now sell allowances to the rate-limited sector, lowering that sector's costs. Because the rate-limited sector increases its generation, it earns more allowances, so total emissions increase.

2.3.4. Relaxing assumptions

Of course, these results apply to the given context of identical regions with regulations that are different but are equally stringent

in autarky. We expect the result of greater flexibility increasing emissions to be robust to a variety of heterogeneity. An exception, for Proposition 4 (as indicated by Fischer 2003), could be if the emission regulation were so much more stringent in the mass region than in the rate region that the allowance price started out lower in the rate region than in the mass region. In such a situation, introducing rate-mass allowance trade could in theory cause generation to shift from the rate region to the mass region, lowering emissions instead of increasing them. We find this to be the case in the numerical simulations described below. Another exception is the case in which neither the mass region's cap nor the rate region's rate limit binds.

Heterogeneity across regions or states also implies that allowing flexibility can offer non-environmental economic benefits, even if it is bad for emissions. However, when regulators strive to minimize cost heterogeneity in setting state-specific emissions goals (e.g., under the CPP, USEPA intended to select performance standards that each state could meet with similar levels of effort), the expected benefits to trading are also minimized.

A detailed numerical model of the regulated sector is therefore useful, for answering more practical questions: Are the theoretical predictions borne out in a realistic numerical model with price-responsive demand? How much might emissions rise because of the flexibility to trade allowances across regions? How much more stringent must rate-based regulation be for flexibility to lower emissions? What are the net welfare consequences of flexibility mechanisms? We next turn to such a model of the U.S. electricity sector to simulate the effects of different regulatory designs.

3. Numerical model of the US electricity sector

3.1. E4ST description

We employ a version of the power system simulation software known as the Engineering, Economic, and Environmental Electricity Simulation Tool (the E4 Simulation Tool, or E4ST—pronounced “east”). For this project, the authors added features to the software and incorporated them into the next publicly available version. For a more detailed description of E4ST, see Shawhan et al. (2014) and Mao et al. (2016). E4ST is designed to do unusually realistic, detailed simulations of how power systems operate and evolve, and how their operation and costs would respond to different policies, transmission investments, generation investments, natural gas supply investments, input prices, demand patterns, and so on. The model's outputs lend themselves to comprehensive benefit-cost analysis.

Along with the software, the developers of E4ST have also developed models of the three grids that serve almost all electricity customers in the United States and Canada: the eastern, western, and Texas grids. Each of these grid models includes a detailed model of the transmission system and detailed information about the generators, including heat rate (i.e., fuel efficiency), fuel type, emissions rates, and health effects of emissions, among other characteristics. In the tests to date, the simulations' predictions have closely matched observed reality.

E4ST predicts the operation of the grid, and the generators on it, in successive years or multiyear periods. E4ST currently uses a set of 37 representative hours to typify each year or multiyear period. Each representative hour represents between 3 and 412 real hours and is weighted accordingly. The frequency distributions of load, wind, and sun in that set of 37 representative hours closely match the corresponding frequency distributions in the 8760 h of the year on which the representative hours are based. For each representative hour, E4ST solves a highly realistic, engineering- and economics-based optimization problem similar to that solved by power system operators. Simultaneously, generator investment and retirement are optimized, taking into account all 37 representative hours.

For each of thousands of preexisting or potential wind and solar generation facilities in the United States, we have a close approximation

Fig. 3. Model regions for mass caps and rate limits.

of its generation in each representative hour, from detailed hourly high-resolution wind and solar data. We also have an approximation of the electricity demand at each node in each representative hour. Demand responds to prices, and the user can set the shape of the demand curve. We use that to explore the sensitivity of our results to demand responsiveness.

E4ST simulates customizable emissions cap-and-trade programs, emissions prices, and renewable energy portfolio standards of individual jurisdictions or combinations of jurisdictions. It also realistically represents the operation of each hydropower facility, with a user-specifiable minimum generation and maximum generation in each type of hour, and an amount of energy that can be used when it is most valuable in each season or year. Macro and policy variables—including total electricity demand in each region, fuel prices, hydropower limits, regional emissions limits, transmission investments, and policy parameters—are fully adjustable.

The predicted costs and emissions that we can calculate include fuel costs, annual fixed costs, construction costs, CO₂ emissions, premature deaths from generator SO₂ and NO_x emissions, and estimated dollar value of those premature deaths. Some other effects that we can calculate include electricity prices, consumer surplus, producer profits, government revenues, and total surplus. We can disaggregate any of the effects—for example, by region or by generator type. We calculate the estimated mortality effect of each generator, per GWh, by using a detailed air pollution fate and transport model, taking into account each generator's location, effective smokestack height, and emissions rates.

For our purposes, given the complexity and number of scenarios, we restrict our area of interest to the eastern grid in the United States and Canada, known as the Eastern Interconnection, which includes approximately 74% of US and Canadian electricity consumption.

3.2. Scenarios

Our business-as-usual (BAU) scenario has no emissions caps or emissions prices in any part of the United States. It has a CO₂ emissions

cap in the Canadian part of the model, and a renewable energy portfolio standard in the northeastern and mid-Atlantic US states that represents renewable energy commitments made in those states as of January 2016.

We then simulate a CO₂ emissions reduction policy in which one region faces a mass cap while the other has a rate limit. The mass-capped region contains all states northeast and due east of Illinois, plus North Carolina, minus Indiana. The rate-limited region is the rest of the eastern grid region (Fig. 3).⁹ Four summary statistics enable a comparison of the two regions. In the E4ST base case simulations results with no emission limits, total generation was 1.60 TWh in the mass region and 1.67 TWh in the rate region. Total CO₂ emitted from power generation was 0.53 tons per MWh in the mass region and 0.62 tons per MWh in the rate region. Allowance trading *within* each region is allowed in all of our scenarios, but allowance trade *between* the two regions is allowed in only some of our scenarios.

We will refer to pairs of limits according to the mass cap percentage of BAU followed by the rate limit percentage of BAU. For example, the “M70-R70” scenario assumes limits that are 70% of BAU emissions or emissions intensity, respectively, for the mass-capped and rate-limited regions. Subsequent sensitivity analysis varies the limit for one or both regions, to explore the effects of different combinations of regulatory stringency. “Emissions” will refer to CO₂ except where otherwise specified.

In our default parameterization, consumer demand for electricity is price responsive, with an own-price elasticity of -0.4 . We also run the above scenarios assuming demand is perfectly inelastic, to check the effects of demand responsiveness. Electricity trade is always allowed between the rate and mass regions in the model, although it

⁹ This set of state choices is one of two sets in Niemeyer (2016). Both sets are hypothetical, since the CPP was not implemented to the point of requiring states to choose. More than half of the mass-capped states are in the Regional Greenhouse Gas Initiative, which is committed to mass caps. This map matches the theoretical case relatively well, in that the regions have very similar amounts of generation (and of load) and similar average CO₂ per MWh emission values. In addition to the states colored green, small parts of Texas, New Mexico, and Montana are served by the eastern grid and are assumed to be part of the rate-limited region.

is limited by the constraints of the transmission grid. Prohibiting electricity trade between the mass and rate regions would not be realistic, so to explore the role of electricity trade, we add to the current transmission capacity between the rate and mass regions. Specifically, we add six bidirectional 1000-MW direct-current transmission lines connecting the following pairs of adjacent states, where the first is in the rate region and the second in the mass region: SC-NC, TN-KY, IA-IL, IN-IL, IN-OH, WI-MI. Each line has two terminals, one at each end. We place each terminal at one of the highest-voltage nodes in the state, near the state's geographic center.

Our M70-R70 scenario, when rate-mass allowance trade is not allowed and there is no additional transmission capacity, results in allowance prices that are significantly higher in the rate-limited region (\$23/ton CO₂) than in the mass-capped region (\$16/ton CO₂). This M70-R70 scenario of equal percentage reductions in the emission limits in the two regions corresponds roughly to our theoretical autarky example because it has no added transmission capacity, and rate-mass allowance trading is not allowed, though it has price-responsive electricity demand and some electricity transmission capacity. As discussed in the theory section, the higher allowance price in the rate region is to be expected, even if autarky abatement costs were exactly the same in the two regions. All monetary values in this paper are in 2013 US dollars. All tons are short tons. A short ton equals 0.907 metric ton.

We then run a scenario that without rate-mass allowance trading has roughly the reverse allowance price burden and achieves the same total emissions as the M70-R70 scenario. We accomplish this with CO₂ emissions in the mass region capped at 41% of BAU emissions and with emissions intensity (rate) in the rate region limited to 85% of that region's BAU emissions intensity. We will refer to this pair of limits as “M41-R85.” Fig. 4 displays the allowance prices in the M70-R70 scenario and the M41-R85 scenario, without additional flexibility mechanisms. A strategy for reading this figure and the ones that follow is to first look at the vertical bars corresponding to the M70-R70 emission limits, then move on to the vertical bars corresponding to the M41-R85 emission limits.

4. Results

4.1. Effects on CO₂ emissions

Starting with these two base policy scenarios, we next examine the effect of the flexibility mechanisms on emissions. The M70-R70 limits and M41-R85 limits, without trade, each achieve a 27% overall CO₂ emissions reduction. Fig. 5 shows the emission changes, expressed as a

Fig. 4. Allowance prices by scenario and region, without added transmission and without rate-mass allowance trading. M41-R85 is the pair of emission limits that comes closest to reversing the two allowance prices while holding total emissions constant, relative to the M70-R70 limits, assuming no rate-mass trading and no additional transmission capacity.

Fig. 5. Change in CO₂ from added flexibility mechanisms, as share of CO₂ reduction from emissions regulation. A positive percentage means that the flexibility mechanism increases CO₂ emissions. Under the M70-R70 limits, adding transmission reverses 0.5% of the CO₂ reduction from the limits, while adding allowance trade reverses 8% of it and adding both reverses 9% of it. Under the M41-R85 limits, the respective percentages are 3%, -2%, and -1%.

percentage of that reduction, due to the addition of flexibility mechanisms; a positive percentage denotes that the flexibility mechanism increases emissions. Table 1, later in this section, shows the same results that Figs. 4 through 7 do, along with some additional results; it is an alternative source of results information. However, the figures report the flexibility-caused changes as percentages of the changes caused by the imposition of the emission limits, while Table 1 reports the changes in tons or terawatt-hours (TWh).

In the theory section of this paper, Proposition 2 is that electricity trading between differently regulated (but otherwise identical) regions would increase emissions. In the model results, we see that additional electricity trade (i.e. transmission) capacity indeed increases emissions in the M70-R70 scenario, and in the M41-R85 scenario as well. In the approximately 35 scenario pairs simulated, we found that the additional transmission capacity increased CO₂ emissions in all except two scenario pairs. In those two exceptional scenario pairs the following conditions both applied: rate-mass allowance trade was not allowed and the mass cap was much more lax than the rate limit (specifically, 90% mass cap with 70% rate limit, and 70% mass cap with 10% rate limit). Those conditions give the mass-capped region a cost advantage sufficient to make it a net exporter of electricity to the rate-limited region; as a result, additional transmission capacity allows additional generation in the rate-limited region to be crowded out, thus reducing the total allowance allocation.

Proposition 4 implies that, like electricity trading, rate-mass allowance trading would increase emissions. In all of the simulation pairs in which the allowance price prior to rate-mass allowance trading was higher in the rate-limited region than the mass-capped region (which applies unless the mass cap is much more stringent than the rate-based standard), such trading indeed increases emissions. Consistent with the theory section, rate-mass allowance trading equalizes the allowance prices. If the allowance price without rate-mass trading is higher in the rate region than in the mass region, the allowance price equalization makes the generators in the rate region more competitive relative to those in the mass region, so they produce more electricity and thereby earn more emissions allowances. For example, as shown in Fig. 5, in the M70-R70 case, rate-mass allowance trading reverses 8% of the emissions reduction that would otherwise result from the emissions limits.

However, as explained after Proposition 4 in the theory section, in cases in which the allowance price prior to rate-mass allowance trading is lower in the rate region than the mass region (reflecting a mass cap

Table 1
Projected effects of flexibility mechanisms, by scenario, in 2035.

Outcome	Region	Mass 70%, rate 70% scenarios				Mass 41%, rate 85% scenarios			
		Levels in base M70-R70 scenario	Effects of changes			Levels in base M41-R85 scenario	Effects of Changes		
			More transmission capacity	Rate-mass allowance trade	Both together		More transmission capacity	Rate-mass allowance trade	Both together
CO ₂ Price (\$/short ton)	Mass	15.8	−0.5	+3.0	+2.7	21.7	−0.3	−2.3	−2.5
	Rate	23.1	−0.1	−4.4	−4.6	14.9	−0.2	+4.5	+4.3
Generation (TWh)	Mass	1395	−4	−89	−97	1216	−19	+33	+26
	Rate	1778	+6	+70	+79	1932	+19	−15	−9
	Union	3173	+2	−20	−17	3147	+1	+17	+17
CO ₂ (M short tons)	Mass	592	+0	−114	−115	347	+0	+74	+72
	Rate	770	+3	+144	+149	1016	+10	−82	−77
	Union	1362	+3	+30	+34	1363	+10	−8	−5
<i>Surplus</i>									
Internal Surplus (\$M)	Union	11,560,882	+146	+439	+606	11,559,717	+224	+252	+454
CO ₂ benefits (\$M)	Union	−74,638	−142	−1653	−1887	−74,680	−554	+446	+257
Sum of Surpluses (\$M)	Union	11,486,244	4	−1214	−1282	11,485,037	−330	698	711

Notes: All dollar values in this article are 2013 US dollars. “Levels” means quantities, not changes in quantities. “More Transmiss’n Capac.” means adding transmission capacity between the rate and mass regions. “Rate-Mass Allownce Trade” means allowing trade of emission allowances between the rate and mass regions. “Both Together” means both adding transmission capacity and allowing rate-mass allowance trading. “Union” means the mass and rate regions together, which constitute the US portion of the Eastern Interconnection. “M” denotes “millions.”

that is much more stringent than the rate limit), rate-mass allowance trade could have the opposite effect and lower emissions. In the reported and unreported simulation results, the allowance prices without rate-mass trading perfectly predict whether such trading raises or lowers emissions, in accordance with the hypotheses just stated. For example, in the M41-R85 case, the two regions’ allowance prices without rate-mass trading are approximately reversed relative to those in the M70-R70 case, and allowing rate-mass allowance trade amplifies the emissions reductions from the CPP-like emissions limits rather than partially counteracting them. It amplifies them by just over 2% as shown in Fig. 5.

Based on our simulations, two CO₂ limit combinations at which rate-mass allowance trading would neither increase nor decrease emissions are approximately 70% mass cap with 87% rate limit, and 38% mass cap with 70% rate limit. Starting from either of those combinations, lowering the mass cap or raising the rate limit would create a situation in which trading would decrease, rather than increase, CO₂ emissions. In summary, the results suggest that allowing rate-mass trading is likely to increase overall carbon emissions unless the mass program is much more stringent than the rate program, and that adding transmission capacity between the regions is likely to increase overall carbon emissions unless the mass program is much less stringent than the rate program.

Fig. 6. Change in generation from added flexibility mechanisms, as share of generation reduction from emissions regulation. Under the M70-R70 regulations, allowing rate-mass trading reduces generation. Under M41-R85, it increases generation.

4.2. Effects on total generation

Generation changes are important in their own right, and also because of their influence on emissions. The net effects of added flexibility on total generation are depicted in Fig. 6, where the changes are again represented as a share of the total generation reduction induced by the regulations alone; a positive percentage denotes that the flexibility mechanism increases generation. Under both the M70-R70 and M41-R85 regulations, adding transmission capacity reverses a small portion of the regulation-induced reductions in generation and in emissions, by increasing the amount of generation that can occur in the rate-regulated region for satisfying demand in the mass-capped region.

Rate-mass trading has a more surprising effect. Comparison of Figs. 6 and 5 reveals that the effects of rate-mass allowance trading on generation are opposite of its effects on emissions. With the M70-R70 regulations, the allowance price without rate-mass allowance trading is lower

Fig. 7. Regional generation changes from added flexibility mechanisms, as a share of generation reduction from emissions regulation. A positive percentage means that the flexibility mechanism increases generation in that region. Under the M70-R70 limits, allowing rate-mass trading shifts generation from mass region to rate region and Canada. Under the M41-R85 limits, it shifts it in the opposite direction.

in the mass-capped region than in the rate-limited region. Rate-mass trading consequently drives up the allowance price in the mass-capped region, where generation is more responsive to it, as will be explained in the next subsection. This reduces total generation. On the other hand, the total generation increases with the M41-R85 regulations. One implication of this pattern is that the emissions response is dominated by a composition effect rather than a total size effect: it depends on the location of generation and often moves in the opposite direction from the total amount of generation.

4.3. Regional decomposition of effects on total generation

As previously noted, in both our M70-R70 and our M41-R85 scenarios, net electricity trade is in the same direction, from the rate-limited region toward the mass-capped region. The direction of allowance trade, however, depends on the relative allowance prices. Both kinds of trade flows influence what the regional change in generation will be when additional flexibility is introduced. Fig. 7 shows the changes in generation by region and scenario, reported as a share of the reduction in total generation attributed to the emission limits alone, which were shown in Fig. 6. (The reduction attributed to the M70-R70 limits is 2%, as is the reduction attributed to the M41-R85 limits, when rate-mass allowance trading is not allowed and there is no additional transmission capacity.) A positive percentage in Fig. 7 denotes that the flexibility mechanism increases generation in that region. Here we see that in all four cases involving rate-mass trading, the mass-capped region adjusts its generation to a greater extent than does the rate-limited region, as a result of the implicit subsidy the rate limit provides for generation in the rate region, a subsidy which grows with the allowance price and hence reduces its net effect on rate-region generators' marginal costs per MWh. Meanwhile, the change in total emissions depends purely on the change in generation in the rate-limited region, which determines how many more (or fewer) allowances are allocated to the system.

4.4. CO₂ damage

Under the M70-R70 regulations, which are based loosely on the US Clean Power Plan, adding rate-mass allowance trading increases estimated CO₂ damage by approximately 3.8 times as much as it increases internal (i.e. private) surplus, assuming that the damage from CO₂ is \$55 per ton, as estimated by the [Interagency Working Group on Social Cost of Carbon \(2015\)](#). The transmission capacity we added increases CO₂ damage by approximately the same as it increases internal surplus.

4.5. SO₂ and NO_x damage

We also estimated SO₂ and NO_x health damage in each scenario, in two ways. The first way was to assume that the average damages per ton of SO₂ and NO_x are equal to the estimated national average damage per ton values derived from [USEPA \(2013\)](#), in both regions. These values are \$49,629 per ton of SO₂ and \$7373 per ton of NO_x ([Shawhan, 2018](#)). Under this assumption, the estimated SO₂ and NO_x damage move in the same direction as does estimated CO₂ damage, since generators with higher CO₂ emission rates tend to also have higher SO₂ and NO_x emission rates. Counting the changes in SO₂ and NO_x damage roughly doubles the change in total estimated environmental damage. The main result is that, if the SO₂ and NO_x emissions were equally harmful in both regions, considering the damages from them would magnify the changes in total social surplus in Table 1. The sole exception is that, under the M70-R70 regulations, it would change additional transmission capacity from being slightly beneficial to being harmful. However, unlike with CO₂, the average damages per ton of SO₂ and NO_x emitted are equal between the two regions, which brings us to the next way.

The second way to we estimated SO₂ and NO_x damage was to use the air pollution transport model from the Climatological Regional

Dispersion Model ([NRC 2010](#)) to estimate damage. This took into account the location and effective smokestack height of each generator, so damage per ton became heterogeneous. Resulting average estimated damages per ton of SO₂ and NO_x emitted in the mass-capped region were approximately 35% higher than per ton emitted in the rate-limited region, because of higher population density in the mass-capped region. This reversed the signs of the SO₂ and NO_x damage changes that resulted from allowing rate-mass trading, under both M70-R70 and M41-R85. This illustrates that a policy change that shifts the location of non-uniformly mixing emissions can reduce their quantity but increase the damage from them, or vice versa. Under the M41-R85 regulations, this effect was large enough that counting SO₂ and NO_x damages changed rate-mass trading from being beneficial to being harmful. This result occurred only because, with the particular rate and mass regions assumed in the numerical modeling, the average damage per ton of SO₂ and NO_x emissions is greater in the mass region than in the rate region.

All the results shown in this paper assume that demand is price-responsive, with an own-price elasticity of -0.4 . We also simulated the same policies with price-unresponsive demand (elasticity of zero), and found that the resulting signs of the internal surplus and CO₂ surplus values are the same as in Table 1.

5. Discussion

Our analysis raises some important concerns about the desirability of facilitating greater trade—in electricity or in emissions allowances—between differently regulated regions. Insofar as different jurisdictions propose to link mass- and rate-based programs, there are some measures available for ensuring that overall emissions do not increase because of linkage. One is to require that states (or countries, municipalities, or sectors) with rate-based programs convert to mass-based standards prior to trading. This option encourages states to move toward more efficient emissions trading policies, but it may discourage some states from engaging in allowance trade, which avoids some unwarranted trade but also forgoes some legitimate gains from trade. A second is to require states to tighten their standards prior to rate-mass allowance trade; this approach addresses the overall goal of preserving emissions reductions but does not address the distorting effect of having production subsidies.

The other options involve trade-related measures. For example, one could apply an exchange rate to trades between mass-capped and rate-limited states; this option essentially discourages trade unless it is justified by significant abatement cost differences. It is less strict than a ban on cross-regime trading but introduces its own distortions. Recent research on exchange rates shows that they can also have uncertain effects on emissions, depending on the direction of trade flows ([Burtraw et al. 2013](#)).

Alternatively, one could encourage states that have mass-based programs to allocate allowances based on performance benchmarks (output-based allocation) when they trade with states having rate-based programs. This option has the potential to address the problems of production shifting that result from the combination of electricity and rate-mass allowance trade, but in the long run it distorts electricity prices downward, and it can create state-specific electricity subsidies (to the extent that performance benchmarks differ). Furthermore, this option asks states with existing mass-based programs to forgo auction revenue that may fund energy efficiency programs and other public expenditures. It is also inefficient from a general equilibrium perspective because it shuts off a revenue source that may allow other, more distorting taxes to be reduced.

Finally, one could encourage states with mass-based standards to implement border carbon adjustments, which has the advantage of dealing with the carbon leakage that results from electricity trade and is exacerbated by rate-mass allowance trade, while retaining the ability of mass-capped states to use emissions auction revenues for their preferred

purposes. There is some precedent for this action in California's emissions trading program.

In future research, researchers could explore how these design and linking decisions interact with other policies and regulations, since the larger context is also important (Fischer and Preonas 2010). For example, consider the value of energy efficiency (EE) investments under different regulatory regimes. In theoretical analyses, a sometimes useful assumption is that consumers have fixed demand for energy services, but that policy interventions can reduce the energy required to achieve those services. (Fell et al. 2015 employ this assumption in showing that EE crediting can offset distortions from rate-based allocations, in the absence of trade.) Incorporating this change into the theoretical model presented in this paper, we find that without the possibility of electricity trade, the benefits of investing in EE measures are identical across states with different regimes, even if rate-mass trading is allowed. Demand reduction lowers in-state power production needs and lowers regulatory compliance costs. However, electricity trade breaks the link between local production and local demand, causing EE incentives to diverge. In-state demand reduction then lowers interstate production needs, lowering both electricity and allowance prices and changing net exports of electricity and allowance revenues. Since many states do use allowance auction revenues to fund EE improvements, the interaction between such investments and rate-mass trading could be interesting to explore.

Acknowledgements

Fischer is grateful for the support of the Mistra Carbon Exit program and European Community's Marie Skłodowska-Curie International Incoming Fellowship, 'STRATECHPOL – Strategic Clean Technology Policies for Climate Change', financed under the EC Grant Agreement PIIF-GA-2013-623783. Mao and Shawhan are grateful to Gurobi Optimization for the use of Gurobi Optimizer; Energy Visuals, Inc. for the use of data from their Transmission Atlas and FirstRate products; and the US Department of Energy, US National Science Foundation, New York Independent System Operator, and Power Systems Engineering Research Center for past support of building the simulation tools and models used in this paper. They also thank participants at the Workshop on Environmental Regulation: Emission trading scheme and market power, hosted by ETH–Zurich (Sept 29–30, 2017), and at the Energy Modeling Forum Workshop held by the Brookings Institution, Washington DC (February 3, 2017). They also thank the following colleagues who have been fellow builders of the E4ST software and models: Carlos Murillo-Sanchez, Paul D. Picciano, William D. Schulze, Di Shi, John T. Taber, Robert J. Thomas, Daniel J. Tylavsky, Yujia Zhu, Ray D. Zimmerman, Zamiyad Dar, Andrew Kindle, Nan Li, Yingying Qi, and Richard E. Schuler. All of the authors are grateful to two anonymous reviewers who provided excellent suggestions, and to the EMF 32 organizers.

Declarations of interest

None.

Appendix A

Proof of Proposition 2. Formally, production in R from source i is $q_{iR} = (p_R - t_R(u_i - r) - a_i)/b_i$. The allowance price t_R is endogenous to the total level of production, as equilibrium requires $u_c q_{cR} + u_d q_{dR} = r Q_R$ where $Q_R = q_{cR} + q_{dR}$. In the equilibrium, given this endogenous t_R , $Q_R = \frac{(u_d - u_c)}{b_d(r - u_c)^2 + b_c(r - u_d)^2} (p_R(u_d - u_c) - a_c(u_d - r) - a_d(r - u_c))$. Clearly, $\partial Q_R / \partial p_R > 0$.

Production in M from source i is $q_{iM} = (p_M - t_M u_i - a_i)/b_i$. The allowance price t_M is endogenous to the total level of production (and thereby the price of electricity), as equilibrium requires $u_c q_{cM} + u_d q_{dM} = A$ and $Q_M = q_{cM} + q_{dM}$. In the equilibrium, $t_M = \frac{p_M(b_d u_c + b_c u_d) - a_c b_d u_c - a_d b_c u_d - A b_c b_d}{b_d(u_c)^2 + b_c(u_d)^2}$, so $\partial t_M / \partial p_M > 0$; the emissions price thus falls if the electricity price falls in the mass-capped region.

Proof of Proposition 4. Derivations¹⁰ show that with otherwise identical regions and equivalent but asymmetric regulations, the difference in emissions between an equilibrium with cross-regime electricity trade versus without it is

$$E_R^{\text{Trade}} - E_R^{\text{NoTrade}} = \frac{r^2}{\chi} (D(b_c(u_d - r) + b_d(u_c - r)) + (a_c - a_d)(u_d - u_c))$$

where

$$\chi = b_c((r - u_d)^2 + u_d^2) + b_d((r - u_c)^2 + u_c^2) > 0$$

More derivations show that

$$E_R^{\text{Flex}} - E_R^{\text{Trade}} = (E_R^{\text{Trade}} - E_R^{\text{NoTrade}}) \frac{(b_c(r - 2u_d) + b_d(r - 2u_c))^2}{r^2(b_c + b_d)^2 + 4b_c b_d(u_d - u_c)^2} +$$

Therefore, adding rate-mass allowance trade has the same directional effect on emissions as does electricity trade, which Proposition 2 found to be positive.

We can also put a clear sign on the effects by stating the following relationships. The exercise is akin to calibrating the model to a baseline, but with general parameter values. Let $\gamma \equiv b_c/b_d$ be the ratio of the supply slopes, and let $\alpha = q_d^0/D$ be the share of dirty energy in the baseline. Let us observe the baseline electricity price to be P^0 . From these relationships we can back out the cost function variables.

$$\begin{aligned} b_c &= \gamma b_d \\ a_c &= P^0 - \gamma b_d D(1 - \alpha) \\ a_d &= P^0 - b_d D\alpha \end{aligned}$$

Substituting, we get that

$$E_{PS}^{\text{Trade}} - E_{PS}^{\text{NoTrade}} = \frac{r^2}{\chi} (D b_d (1 + \gamma)(\alpha u_d + (1 - \alpha)u_c - r)) > 0$$

The term $\alpha u_d + (1 - \alpha)u_c$ is the average emissions rate in the baseline, which is higher than the rate applied by the regulation.

References

- Böhringer, Chris, Rosendahl, Knut-Einar, 2010. Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *J. Regul. Econ.* 37 (3), 316–325.
- Burtraw, Dallas, Fischer, Carolyn, Munnings, Clayton, Palmer, Karen L., Paul, Anthony, Richardson, Nathan, Shih, Jhih-Shyang, Williams, Robertson C., 2014. *Comments to the US Environmental Protection Agency on Its Proposed Clean Power Plan. RFF Report*, December 1, 2014. Resources for the Future, Washington, DC.
- Burtraw, Dallas, Palmer, Karen, Munnings, Clayton, Weber, Paige, Woerman, Matt, 2013. *Linking by degrees: incremental alignment of cap-and-trade markets. RFF Discussion Paper 13–04*. Resources for the Future, Washington, DC.
- Bushnell, James, Holland, Stephen P., Hughes, Jonathan, Knittel, Christopher, 2017. Strategic policy choice in state-level regulation: the EPA's clean power plan. *Am. Econ. J. Econ. Policy* 9 (2):57–90. <https://doi.org/10.1257/pol.20150237>.
- Southern Company, January 21, 2016. "Comments on EPA's Federal Plan Requirements for Greenhouse Gas Emissions from Electric Utility Generating Units Constructed on or Before January 8, 2014; Model Trading Rules; Amendments to Framework Regulations; Proposed Rule; 80 Fed. Reg. 64,966 (October 23, 2015); Docket ID No. EPA-HQ-OAR-2015-0199." Comments submitted to US Environmental Protection Agency.
- Fell, Harrison, Kaffine, Daniel, Steinberg, D., 2015. *Energy Efficiency and Emissions Intensity Standards* (Colorado School of Mines).
- Fischer, Carolyn, 2001. *Rebating environmental policy revenues: Output-based allocations and tradable performance standards. Discussion Paper 01–22*. Resources for the Future, Washington, DC.
- Fischer, Carolyn, 2003. *Combining rate-based and cap-and-trade emissions policies. Climate Policy* 3S2, S89–109.
- Fischer, Carolyn, Fox, Alan K., 2007. *Output-based allocation of emissions permits for mitigating tax and trade interactions. Land Econ.* 83 (4), 575–599.

¹⁰ From here, the algebra becomes more complicated, so we will report the key differences in scenarios, and note that Mathematica is used to solve the system; the Notebook file is available by request.

- Fischer, Carolyn, Newell, Richard G., 2008. Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manag.* 55 (2), 142–162.
- Fischer, Carolyn, Preonas, Louis, 2010. Combining policies for renewable energy: is the whole less than the sum of its parts? *Int. Rev. Environ. Res. Econ.* 4 (1), 52–92.
- Holland, Stephen P., Hughes, Jonathan E., Knittel, Christopher R., 2009. Greenhouse Gas Reductions under Low Carbon Fuel Standards? *Am. Econ. J. Econ. Pol.* 1 (1): 106–146. <https://doi.org/10.1257/pol.1.1.106>.
- Interagency Working Group on Social Cost of Carbon, 2015. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*. US Government, Washington, DC.
- Lange, Ian, Maniloff, Peter, 2017. Updating allowance allocations in cap-and-trade: evidence from the NO_x budget program. Colorado School of Mines, July 20.
- Mao, Biao, Shawhan, Daniel, Zimmerman, Ray, Yan, Jubo, Zhu, Yujia, Schulze, William, Schuler, Richard, Tylavsky, Daniel, 2016. The Engineering, Economic and Environmental Electricity Simulation Tool (E4ST): Description and an illustration of its capability and use as a planning/policy analysis tool. *Proceedings of the 49th Annual Hawaii International Conference on System Sciences*. Computer Society Press, pp. 2317–2325.
- National Research Council (NRC), 2010. *Hidden Costs of Energy*. National Academies Press, Washington, DC.
- Niemeyer, Victor, 2016. State-Level Modeling of Clean Power Plan Compliance Pathways with EPRI's US-REGEN Model. RFF-EPRI Seminar on Modeling the Clean Power Plan. February 11, 2016. Electric Power Research Institute (EPRI), Washington, DC.
- Shawhan, Daniel L., 2018. Co-Emission and Welfare Effects of Electricity Policy and Market Changes: Results from the EMF 32 Model Intercomparison Project. *Energy Econ.* <https://doi.org/10.1016/j.eneco.2018.03.034> in this issue.
- Shawhan, Daniel L., Taber, John T., Shi, Di, Zimmerman, Ray D., Yan, Jubo, Marquet, Charles M., Qi, Yingying, Mao, Biao, Schuler, Richard E., Schulze, William D., Tylavsky, Daniel J., 2014. Does a detailed model of the electricity grid matter? Estimating the impacts of the regional greenhouse gas initiative. *Resour. Energy Econ.* 36 (1):191–207 January. <https://doi.org/10.1016/j.reseneeco.2013.11.015>.
- U.S. Environmental Protection Agency (USEPA), January 2013. Estimating the benefit per ton of reducing PM_{2.5} precursors from 17 sectors. <https://www.epa.gov/sites/production/files/2014-10/documents/sourceapportionmentbpttsd.pdf>.
- Viaciulis, Rolandas, 2017. Linking the Alberta emissions trading scheme: difficult but possible. CIRL Occasional Paper #58 (March 2017). Canadian Institute of Resource Law, Calgary.