Regional Carbon Policies in an Interconnected Power System: How Expanded Coverage Could Exacerbate Emission Leakage

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Abstract

Interconnected regional electricity markets are often subject to asymmetric carbon policies with partial coverage for CO_2 emissions. While the resulting problem of carbon leakage has been well studied, its mitigation has received relatively less attention. We devise a proactive carbon policy via a bi-level modelling approach by considering the impact of an emission cap that limits the cost of damage from a regional power market. In particular, a welfare-maximising policymaker sets the cap when facing profit-maximising producers and the damage costs from their emissions at two nodes. A partial-coverage policy could degrade maximised social welfare and increase total regional CO_2 emissions with potential for carbon leakage due to a higher nodal price difference. A modified carbon policy that considers CO_2 emissions from both nodes tightens the cap, which increases maximised social welfare and decreases total CO_2 emissions vis-à-vis the partial-coverage policy, albeit at the cost of greater scope for carbon leakage as it causes nodal prices to diverge. As a compromise, an import-coverage policy, implemented by California, that counts only domestic and imported CO_2 emissions could alleviate carbon leakage at the cost of lower maximised social welfare with higher total emissions vis-à-vis the modified-coverage policy.

Keywords: Carbon leakage, regional electricity markets, bi-level modelling

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1. Introduction

Under the current version of the Paris Agreement, participating countries set their own emission-reduction targets and choose their own strategies for achieving these targets (UNFCCC, 2015). This protocol could result in a variety of different policies across the globe including the existing cap and trade (C&T) programs. Besides the question of setting socially optimal carbon policies in a deregulated industry (Siddiqui et al., 2016; Pineda et al., 2018), there is also growing concern that policies with disparate stringencies will lead to carbon leakage, which is defined as the displacement of emissions from a region subject to a tighter regulation to regions with less regulation. The electricity industry is particularly vulnerable to such an outcome due to the misalignment of the territory of a regional power market and the regulatory jurisdiction of environmental agencies. In the U.S., such examples include California and the Pennsylvania-New Jersey-Maryland (PJM) Interconnection. PJM spans thirteen states and the District of Columbia (PJM, 2018), yet only two of these states, i.e., Maryland and Delaware, are covered by the emission cap set by the Regional Greenhouse Gas Initiative (RGGI) (C2ES, 2018). The carbon-leakage situation in California could also be further exacerbated by the introduction of the real-time Energy Imbalance Market (EIM) as it allows out-of-state imports from uncapped regions to serve demand in the CAISO territory (CARB, 2017). Furthermore, the EU has established the Energy Community that gathers some non-EU member countries with the purpose of integrating them into the EU electricity market (Energy Community, 2018); however, since these non-EU countries are not subject to the EU Emissions Trading System (ETS), they are potentially at risk of being exposed to carbon leakage (Višković et al., 2017).

Carbon leakage resulting from unilateral policies has been widely discussed in the literature as it can undermine emission-reduction objectives, and since CO_2 emissions are damaging globally independently of their origin, it is necessary to complement unilateral policies with measures for carbon-leakage mitigation. On a global level, several studies estimate the magnitude of leakage that could occur as a result of such unilateral policies (Paltsev, 2001) and how leakage could further be exacerbated as a result of free trade (Kuik and Gerlagh, 2003). Especially at risk are carbon-intensive sectors subject to international trade, e.g., manufacture of chemical products, manufacture of iron and steel, and mining and extraction of fossil fuels (European Commission, 2014).

To safeguard the environmental effectiveness of unilateral policies, a variety of corrective measures has been proposed, including border carbon adjustment that contains a carbon tariff on emissions from production of goods imported from an unregulated region or a production rebate for emissions from production of goods exported to unregulated regions, e.g., Markusen (1975) and Hoel (1996). Furthermore, Copeland (1996) finds that if a carbon tariff is more finely targeted to the pollution content of the imported product, then it could incentivise more-intensive emitters to improve their production processes. Although carbon tariffs have not been implemented yet, studies using computable general equilibrium models of global trade suggest that these have potential for reducing carbon leakage. For instance, Böhringer et al. (2012) apply a carbon tariff based on average emissions of the unregulated region and find that carbon leakage could be further reduced if the tariffs are specially tailored to firms' emissions (Böhringer et al., 2017). Despite proving effective in numerical studies, tariffs could be legally and politically challenging to implement as their introduction could lead to retaliation from countries affected by carbon tariffs, which could result in trade wars (Böhringer et al., 2017).

The allowance allocation in a C&T plays an important role in carbon-leakage mitigation. Output-based updating has been prominently discussed in the literature due to its leakage mitigation potential compared to other forms of allocation, e.g., auctions (Fischer and Fox, 2007). In the context of the California electricity market C&T, Bushnell and Chen (2012) compare output-based updating allocation with an alternative approach based on auctions. The study finds that if the updating is based on an average industry emission rate, then the output-based allocation reduces leakage in comparison to the auction. By contrast, a more finely targeted updating based on fuel types could lead to a similar magnitude of leakage with permit prices above the auction level. Another example of disparate regulation stringency that could result in carbon leakage arises in the context of plant vintage differentiation in states with a C&T under the U.S. Clean Power Plan. In particular, Palmer et al. (2017) find that allocating allowances solely to natural gas producers is the most effective way of reducing leakage, albeit closely followed by allocating allowances to both natural gas and coal producers. In practice, the EU uses auctioning as a form of allowance allocation but allocates some allowances free of charge to sectors (other than power generation) exposed to the risk of carbon leakage (European Commission, 2018b). The free allowance allocation is benchmarked on the most efficient installation in each sector (European Commission, 2018b).

The mandatory purchase of allowances for emissions associated with electricity imported from an unregulated region has been implemented in California (Title 17, California Code of Regulations, sections 95801-96022). However, studies have shown that even with this approach, the problem of carbon leakage might persist due to contract shuffling. For instance, Chen et al. (2011) examine all-inclusive coverage plans encompassing emissions from production in the regulated area and from imports into the regulated area. These are compared to more conventional source-based (covering emissions only from production in the regulated area) and load-based (covering emissions only from total consumption in the regulated area) plans. The authors find that all-inclusive plans result in more regulated emission reduction compared to the conventional alternatives; however, these do not prove to be very effective at reducing carbon leakage as the emissions for the entire region remain unchanged.

Implementation of corrective measures for leakage mitigation alongside unilateral policies constitutes the second-best solution vis-à-vis global carbon pricing. In contrast to the extant literature, we explore a second-best solution in which a cap is optimally determined by a regulator with consideration of minimising emission damage caused by leakage. Specifically, we focus on a regional electricity market represented by two nodes connected by a congested line. The policymaker may implement a C&T that has jurisdiction over only one of the nodes. The node[1] under policymaker's

[1]The setting resembles the situation faced by California, see Section 2.1.

jurisdiction is a net importer of power from the unregulated node, which has cheaper but dirtier generation. In addition, due to the fact that CO_2 is a global pollutant, its resulting damage is not limited to the node where the emission takes place. The question that arises from this context is: *Which emissions should be considered damaging for the node under the policymaker's jurisdiction when setting the socially optimal cap for the C&T?*

To answer this question, we compare a benchmark *full*-coverage policy with three different limited-coverage policies under which the policymaker can choose to take account of damage from emissions from (i) the regulated node only (known as *partial* coverage), (ii) both nodes (*modified* coverage), and (iii) the regulated node plus imports from the unregulated node (*import* coverage). The analysis is based on a bi-level model in which the policymaker at the upper level determines the socially optimal cap for the node participating in the C&T; at the lower level, two producers (one at each node) compete to sell their output while an independent system operator (ISO) manages the grid in a socially optimal way. The lower level includes a market-clearing condition for the C&T. Under each coverage policy, we identify the optimal emission cap, production quantities, the carbon permit price, and the marginal value of transmission capacity. The marginal value of transmission capacity (the dual variable of the transmission constraint) is used as a proxy to measure the potential for carbon leakage under each coverage. We prove analytically that the partial-coverage policy increases total regional emissions and is also subject to a higher risk of carbon leakage vis-à-vis full coverage. In mitigating total emissions, the modified-coverage policy sets a tighter emission cap at the regulated node, which actually increases the potential for leakage relative to the partial-coverage policy. Finally, by targeting only those emissions imported from the unregulated node, the import-coverage policy reduces leakage vis-à-vis modified coverage at the expense of a higher level of total regional emissions.

The structure of the remainder of this paper is as follows. Section 2 lays out the assumptions of our modelling framework, formulates the problem, analytically derives optimal emission caps under four different policies, and provides comparative statics for which proofs are in the appendix. Section 3 provides numerical examples to illustrate key results and to compare outcomes under alternative emission caps. Finally, Section 4 summarises the paper's contributions and indicates directions for future research in this area.

2. Analytical Model

2.1. Assumptions

We assume a regional electricity market with two nodes, $j = E, W$. Each node j has its own inverse-demand function, $A_j - B_j x_j$, where $A_j > 0$ (in \$/MW) is the vertical intercept, $B_j > 0$ (in \$/MW^2) is slope parameter, and x_j (in MW) is the total energy consumption. The inverse-demand function represents the maximum willingness to pay to consume x_j MW of power at node j. The power sector at node j is perfectly competitive and produces power at total cost $C_j y_j$, where $C_j > 0$ (in \$/MW) is the levelised cost of generation and y_j (in MW) is node j's production. A single transmission line of capacity $K > 0$ (in MW) connects the two nodes, and an ISO controls the net power flow to node E on the transmission line, f (in MW), in order to maximise social welfare. Each node's power sector has a CO_2 emission rate, $R_j \geq 0$ (in t/MW, where "t" is the SI abbreviation for "metric ton"), and the cost of damage from emissions is quadratic in the total system emissions, $\frac{1}{2}D\left(\sum_j R_j y_j\right)^2$, where $D \geq 0$ (in \$/t^2) reflects the cost of the externality (Requate, 2006). Given an emission cap of $z \geq 0$ (in t), this power sector determines the profit-maximising production level at each node along with the optimal net flow to node E. The emission cap is set by a welfare-maximising policymaker at the upper level who anticipates the industry equilibrium at the lower level. Since the policymaker is unable to intervene directly in the sector's operations at the lower level, i.e., it has no control over y_j or f, it can only indirectly align the private incentives of industry with social ones by selecting z. The consequence of the emission cap is that producers must pay a rate of ρ (in \$/t) to cover their emissions, where ρ is the shadow price on the C&T constraint.

We model a single representative time period without uncertainty in either demand or production. In order to ensure interior solutions with a congested transmission line and to analyse an economically non-trivial situation in which the high-consumption node E has relatively expensive but less-polluting generation (and *vice versa* for node W), we assume $A_E > A_W > C_E > C_W > 0$, $R_W > R_E$, and $\frac{A_E}{B_E} > \frac{A_W}{B_W}$. We ensure that node W is not "too" expensive, i.e., cost of production at node W inclusive of the marginal cost of damage from emissions does not exceed that at node E: $0 \leq D < \check{D} \equiv \frac{(C_E - C_W)B_E B_W}{(R_W - R_E)[B_E R_W (A_W + B_W K) + B_W R_E (A_E - B_E K)] + (R_E C_W - R_W C_E)(R_E B_W + R_W B_E)}$.[2] Likewise, we rule out a transmission line that is "too" big, i.e., it is smaller than the optimal import at node E if all production occurred at node W: $0 \leq K < \check{K} \equiv \frac{B_W(A_E - C_W) + DR_W^2(A_E - A_W)}{B_E B_W + DR_W^2(B_E + B_W)}$.

The assumptions related to a capped region with relatively less-polluting generation mix interconnected and dependent on imports from an uncapped region with relatively more-polluting generation mix resemble some real electricity markets. One important example is the California electricity market. In 2015, CO_2 emissions from the electricity sector (in-state generation and imports) accounted for 19% of total emissions in California (CARB, 2017). Of this, approximately 40% was due to imported electricity (CARB, 2017) despite the fact that imported electricity deriving from polluting sources covered not more than 24% of California's electricity consumption[3] (California Energy Commission, 2018). Relatively high-polluting imported electricity compared to the electricity generated in California is due to the fact that a substantial part of imported electricity derives from coal-fired power plants, whereas California's production from thermal sources predominantly derives from natural gas.

In order to investigate the consequences of partial coverage, we will formulate a total of four coverage policies as follows:

Full Coverage (PC) This is the socially optimal benchmark in which the policymaker has

[2]This comes from requiring the marginal cost of generation at node W, $C_W + DR_W(R_E y_E + R_W y_W)$, to be less than that at node E, $C_E + DR_E(R_E y_E + R_W y_W)$.

[3]The reason why we say "not more than 24%" is because, according to California Energy Commission (2018), a large part of imported electricity derives from so-called "Unspecified Sources," which could be natural gas, coal, and/or hydropower.

jurisdiction over both nodes E and W. Thus, it sets its emission cap internalising consumer surplus, producer surplus, merchandising surplus from grid operations, and the cost of damage from emissions at both nodes.

Partial Coverage (PC) The policymaker has jurisdiction over only node E and sets its emission cap taking into account only consumer surplus, producer surplus, merchandising surplus from grid operations, and the cost of damage from emissions at node E.

Modified Coverage (MC) This is the same as PC except that the policymaker incorporates the cost of damage from emissions from node-W production into its objective function.

Import Coverage (IC) This is the same as PC except that the policymaker incorporates the cost of damage from emissions from net imports from node W into its objective function.

2.2. Problem Formulation and Analytical Solutions

2.2.1. Full Coverage

This is a bi-level problem in which the lower level consists of industry equilibrium in the presence of a C&T constraint. The upper level is the welfare-maximisation problem of the policymaker in which the decision is to select the optimal emission cap. Starting at the lower level, the industry's problems are as follows:

$$\max_{y_E \geq 0} \quad p_E y_E - (C_E + \rho R_E)\, y_E \tag{1}$$

$$\max_{y_W \geq 0} \quad p_W y_W - (C_W + \rho R_W)\, y_W \tag{2}$$

$$\max_{f} \quad [A_E - B_E y_E]\, f - [A_W - B_W y_W]\, f - \frac{1}{2}\,(B_E + B_W)\, f^2 \tag{3}$$

$$\text{s.t.} \quad -K \leq f \leq K \,:\, \mu^-, \mu^+ \tag{4}$$

$$y_E + f \geq 0 \,:\, \beta_E \tag{5}$$

$$y_W - f \geq 0 \,:\, \beta_W \tag{6}$$

$$0 \leq \rho \perp \quad z - (R_E y_E + R_W y_W) \geq 0 \tag{7}$$

The producers' optimisation problems are (1) and (2), which involve selecting y_j to maximise profit while taking f, p_j, and ρ as given. Note that p_j will equal $A_j - B_j x_j$, but each producer is unable to withhold output in order manipulate the price due to the assumption of perfect competition. Meanwhile, the ISO takes y_j as given (Sauma and Oren, 2006) and selects transmission flow, f, in order to maximise the change in social welfare (3) subject to constraints on transmission capacity and non-negativity of consumption (4)-(6). Given the emission cap, z, set by the policymaker at the upper level, industry must ensure that emissions from regional production comply with this limit. The shadow price, ρ, on (7) serves as an effective tax on both producers. Since each of the three problems is convex, it may be replaced by its Karush-Kuhn-Tucker (KKT) conditions for optimality:

$$0 \leq y_E \perp -\left[A_E - B_E\left(y_E + f\right)\right] + C_E + \rho R_E \geq 0 \tag{8}$$

$$0 \leq y_W \perp -\left[A_W - B_W\left(y_W - f\right)\right] + C_W + \rho R_W \geq 0 \tag{9}$$

$$-\left[A_E - B_E\left(y_E + f\right)\right] + \left[A_W - B_W\left(y_W - f\right)\right] + \mu^+ - \mu^- - \beta_E + \beta_W = 0 \text{ with } f \text{ free} \tag{10}$$

$$0 \leq \mu^- \perp f + K \geq 0 \tag{11}$$

$$0 \leq \mu^+ \perp K - f \geq 0 \tag{12}$$

$$0 \leq \beta_E \perp y_E + f \geq 0 \tag{13}$$

$$0 \leq \beta_W \perp y_W - f \geq 0 \tag{14}$$

We assume that (5)–(6) are met with strict inequalities, which means that $\beta_j^*(z) = 0$ via (13)–(14). Searching for interior solutions parameterised on z, i.e., $y_E^*(z) > 0$ and $y_W^*(z) > 0$, with $f^*(z) = K$, from (11) and (12), we obtain $\mu^{*,-}(z) = 0$ and $\mu^{*,+}(z) \geq 0$. Next, solving (8) and (9) togther with (7) yields:

$$\rho^*(z) = \frac{R_E B_W\left(A_E - C_E - B_E K\right) + R_W B_E\left(A_W - C_W + B_W K\right) - B_E B_W z}{B_W R_E^2 + B_E R_W^2} \tag{15}$$

$$y_E^*(z) = \frac{R_W^2\left(A_E - C_E - B_E K\right) - R_E R_W\left(A_W - C_W + B_W K\right) + B_W R_E z}{B_W R_E^2 + B_E R_W^2} \tag{16}$$

$$y_W^*(z) = \frac{R_E^2\left(A_W - C_W + B_W K\right) - R_E R_W\left(A_E - C_E - B_E K\right) + B_E R_W z}{B_W R_E^2 + B_E R_W^2} \tag{17}$$

Finally, from (10), we obtain:

$$\mu^{*,+}(z) = C_E - C_W + \frac{\left(R_W - R_E\right)\left[B_E B_W z - B_E R_W\left(A_W - C_W + B_W K\right) - B_W R_E\left(A_E - C_E - B_E K\right)\right]}{B_W R_E^2 + B_E R_W^2} \tag{18}$$

Moving to the upper level, the policymaker's problem is to set $z \geq 0$ in order to maximise (19) subject to the lower-level problems as follows:

$$\begin{aligned} \max_{z \geq 0} \quad & A_E\left(y_E + f\right) - \frac{1}{2}B_E\left(y_E + f\right)^2 \\ & + A_W\left(y_W - f\right) - \frac{1}{2}B_W\left(y_W - f\right)^2 \\ & - C_E y_E - C_W y_W - \frac{1}{2}D\left(R_E y_E + R_W y_W\right)^2 \\ \text{s.t.} \quad & (1) - (7) \end{aligned} \tag{19}$$

The terms in (19) comprise social welfare and consist of, in turn, gross consumer surplus at node E, gross consumer surplus at node W, cost of generation at node E, cost of generation at node W, and the total cost of damage from emissions.[4] Note that the upper-level decision variable, z, does not

[4] A complete breakdown of the social welfare involves the *gross consumer surplus* at each node, $A_E\left(y_E + f\right) -$

explicitly appear in the upper-level objective function (19). However, it is implicitly represented through the dependence of the lower-level decision variables on z. Specifically, the policymaker's bi-level problem may be converted to a mathematical program with equilibrium constraints (MPEC) as the lower-level problems may be replaced by their KKT conditions. Since we search for interior solutions, the lower-level solutions parameterised on z, (15)–(18), may be subsequently inserted into the upper-level objective function, thereby yielding the following quadratic programming (QP) problem as all of the lower-level solutions are linear in z:

$$\begin{aligned} \max_{z\geq 0} \quad & A_E\left(y_E^*(z)+f^*(z)\right)-\frac{1}{2}B_E\left(y_E^*(z)+f^*(z)\right)^2 \\ & +A_W\left(y_W^*(z)-f^*(z)\right)-\frac{1}{2}B_W\left(y_W^*(z)-f^*(z)\right)^2 \\ & -C_E y_E^*(z)-C_W y_W^*(z)-\frac{1}{2}D\left(R_E y_E^*(z)+R_W y_W^*(z)\right)^2 \end{aligned} \tag{20}$$

Since (20) is a convex QP with a negative second derivative, the following first-order necessary condition for it is also sufficient:

$$\begin{aligned} & A_E y_E^{*\prime}(z)-B_E\left(y_E^*(z)+K\right)y_E^{*\prime}(z)+A_W y_W^{*\prime}(z)-B_W\left(y_W^*(z)-K\right)y_W^{*\prime}(z) \\ & -C_E y_E^{*\prime}(z)-C_W y_W^{*\prime}(z)-D\left(R_E y_E^*(z)+R_W y_W^*(z)\right)\left(R_E y_E^{*\prime}(z)+R_W y_W^{*\prime}(z)\right)=0 \end{aligned} \tag{21}$$

Solving, we obtain:

$$z^*=\frac{\left[B_E R_W\left(A_W-C_W+B_W K\right)+B_W R_E\left(A_E-C_E-B_E K\right)\right]}{B_E B_W+D\left(R_W^2 B_E+R_E^2 B_W\right)} \tag{22}$$

Inserting z^* into the lower-level parameterised solutions (15)–(18), we obtain the following solutions for $\rho^*(z^*)$, $y_E^*(z^*)$, $y_W^*(z^*)$, and $\mu^{*,+}(z^*)$:

$$\rho^*(z^*) = \frac{D\left[R_E B_W\left(A_E-C_E-B_E K\right)+R_W B_E\left(A_W-C_W+B_W K\right)\right]}{B_E B_W+D\left(R_W^2 B_E+R_E^2 B_W\right)} \tag{23}$$

$$y_E^*(z^*) = \frac{\left(D R_W^2+B_W\right)\left(A_E-C_E-B_E K\right)-D R_E R_W\left(A_W-C_W+B_W K\right)}{B_E B_W+D\left(R_W^2 B_E+R_E^2 B_W\right)} \tag{24}$$

$$y_W^*(z^*) = \frac{\left(D R_E^2+B_E\right)\left(A_W-C_W+B_W K\right)-D R_E R_W\left(A_E-C_E-B_E K\right)}{B_E B_W+D\left(R_W^2 B_E+R_E^2 B_W\right)} \tag{25}$$

$$\begin{aligned} \mu^{*,+}(z^*) = {} & C_E-C_W \\ & -\frac{D\left(R_W-R_E\right)\left[B_E R_W\left(A_W-C_W+B_W K\right)+B_W R_E\left(A_E-C_E-B_E K\right)\right]}{B_E B_W+D\left(R_W^2 B_E+R_E^2 B_W\right)} \end{aligned} \tag{26}$$

$\frac{1}{2}B_E\left(y_E+f\right)^2$ and $A_W\left(y_W-f\right)-\frac{1}{2}B_W\left(y_W-f\right)^2$, the *gross producer surplus* at each node, $p_E y_E$ and $p_W y_W$, *government revenue* collected from sales of C&T permits, $\rho R_E y_E$ and $\rho R_W y_W$, and *net merchandising surplus* for the ISO, $(p_E-p_W)f$. On the other side of the ledger, we have the *consumers' cost of purchasing power* at each node, $p_E(y_E+f)$ and $p_W(y_W-f)$, *generation cost* at each node, $C_E y_E$ and $C_W y_W$, the *generators' cost of C&T permit purchases*, $\rho R_E y_E$ and $\rho R_W y_W$, and the *cost of damage from emissions*, $\frac{1}{2}D\left(R_E y_E+R_W y_W\right)^2$.

It may be verified that the FC solutions are identical to those that would result from central planning, e.g., $\rho^*(z^*)$ would be the same as the implied Pigouvian tax, Dz^*.

2.2.2. Partial Coverage

Under PC, the policymaker also solves a bi-level problem, but the C&T constraint applies only to node-E production. Thus, at the upper level, the policymaker selects the optimal emission cap considering only node-E consumer surplus, producer surplus, and cost of damage from emissions. Starting again from the lower level, we have the following formulations:

$$\begin{aligned} & (1) \\ \max_{y_W \geq 0} \quad & p_W y_W - C_W y_W \qquad (27) \\ & (3) \text{ s.t. } (4) - (6) \\ 0 \leq \rho \perp \quad & z - R_E y_E \geq 0 \qquad (28) \end{aligned}$$

Here, the producer at node W (27) is not subject to the emission cap (28), whereas the problems of the node-E producer and the ISO are unchanged. The new KKT conditions for optimality are:

$$\begin{gathered} (8) \\ 0 \leq y_W \perp -\left[A_W - B_W\left(y_W - f\right)\right] + C_W \geq 0 \qquad (29) \\ (10) - (14) \end{gathered}$$

In order to obtain an equilibrium, we again assume that (5)–(6) are met with strict inequalities, which means that $\hat{\beta}_j(z) = 0$ via (13)–(14). Searching for interior solutions parameterised on z, i.e., $\hat{y}_E(z) > 0$ and $\hat{y}_W(z) > 0$, with $\hat{f}(z) = K$, from (11) and (12), we obtain $\hat{\mu}^-(z) = 0$ and $\hat{\mu}^+(z) \geq 0$. Next, solving (8) and (29) together with (28) yields:

$$\hat{\rho}(z) = \frac{R_E\left(A_E - C_E - B_E K\right) - B_E z}{R_E^2} \qquad (30)$$

$$\hat{y}_E(z) = \frac{z}{R_E} \qquad (31)$$

$$\hat{y}_W(z) = \frac{\left[A_W - C_W + B_W K\right]}{B_W} \qquad (32)$$

Finally, from (10), we obtain:

$$\hat{\mu}^+(z) = \frac{\left[R_E\left(A_E - C_W - B_E K\right) - B_E z\right]}{R_E} \qquad (33)$$

Moving to the upper level, the policymaker sets $z \geq 0$ in order to maximise only the node-E components of (19) subject to the PC lower-level problems, which is then converted to an MPEC as the lower-level problems may be replaced by their KKT conditions. Since we search for interior solutions, the lower-level solutions parameterised on z may be inserted into the upper-level objective function, thereby yielding the following QP:

$$\begin{aligned}\max_{z\geq 0} \quad & A_E\left(\hat{y}_E(z)+\hat{f}(z)\right)-\frac{1}{2}B_E\left(\hat{y}_E(z)+\hat{f}(z)\right)^2 \\ & -C_E\hat{y}_E(z)-\hat{P}_E(z)\hat{f}(z)+(\hat{P}_E(z)-\hat{P}_W(z))\hat{f}(z)-\frac{1}{2}D\left(R_E\hat{y}_E(z)\right)^2\end{aligned} \tag{34}$$

where $\hat{P}_E(z)=A_E-B_E(\hat{y}_E(z)+\hat{f}(z))$ and $\hat{P}_W(z)=A_W-B_W(\hat{y}_W(z)-\hat{f}(z))$. Note that (34) differs from (20) not only by the missing node-W terms but also due to the presence of the $-\hat{P}_E(z)\hat{f}(z)+(\hat{P}_E(z)-\hat{P}_W(z))\hat{f}(z)$ term, which captures the cost to consumers at node E of importing $\hat{f}(z)$ and the ISO's merchandising surplus.[5]

Next, differentiating (34) with respect to z, we obtain the following first-order necessary condition:

$$A_E\hat{y}'_E(z)-B_E\left(\hat{y}_E(z)+K\right)\hat{y}'_E(z)-C_E\hat{y}'_E(z)-DR_E^2\hat{y}_E(z)\hat{y}'_E(z)=0 \tag{35}$$

Solving, we obtain:

$$\hat{z}=\frac{R_E\left(A_E-C_E-B_EK\right)}{B_E+DR_E^2} \tag{36}$$

Inserting $\hat{z}$ into the lower-level parameterised solutions (30)–(33), we obtain:

$$\hat{\rho}(\hat{z}) = \frac{DR_E\left(A_E-C_E-B_EK\right)}{B_E+DR_E^2} \tag{37}$$

$$\hat{y}_E(\hat{z}) = \frac{A_E-C_E-B_EK}{B_E+DR_E^2} \tag{38}$$

$$\hat{y}_W(\hat{z}) = \frac{A_W-C_W+B_WK}{B_W} \tag{39}$$

$$\hat{\mu}^+(\hat{z}) = C_E-C_W+\frac{DR_E^2\left(A_E-C_E-B_EK\right)}{B_E+DR_E^2} \tag{40}$$

The total emissions (including those at node W) under PC are:

$$R_E\hat{y}_E(\hat{z})+R_W\hat{y}_W(\hat{z}) = \frac{R_EB_W\left(A_E-C_E-B_EK\right)+R_W\left(B_E+DR_E^2\right)\left(A_W-C_W+B_WK\right)}{B_W\left(B_E+DR_E^2\right)} \tag{41}$$

[5] The complete breakdown of the social welfare here involves the *gross consumer surplus* at node E, $A_E\left(y_E+f\right)-\frac{1}{2}B_E\left(y_E+f\right)^2$, the *gross producer surplus* at node E, p_Ey_E, *government revenue* collected from sales of C&T permits, ρR_Ey_E, and *net merchandising surplus* for the ISO, $(p_E-p_W)f$. We assume that node E is large enough that the ISO's revenues are fully attributed to its welfare. If the two nodes were more equal in terms of their consumption, then a more equitable split of the merchandising surplus could be accommodated (Huppmann and Egerer, 2015). On the other side of the ledger, we have the *consumers' cost of purchasing power* at node E, $p_E(y_E+f)$, *generation cost* at node E, C_Ey_E, the *generator's cost of C&T permit purchases* at node E, ρR_Ey_E, and the *cost of damage from emissions* at node E, $\frac{1}{2}D\left(R_Ey_E\right)^2$.

2.2.3. Modified Coverage

Under MC, the C&T constraint is again applicable only to node-E production. However, at the upper level, the policymaker selects the optimal emission cap considering only node-E consumer surplus and producer surplus as well as the cost of damage from emissions from both nodes. Thus, it attempts to internalise the cost of damage from total emissions at node W. In terms of the lower-level formulation and equilibrium conditions, they are unchanged from those under PC, i.e., the solution is still (30)–(33). This is because industry at the lower level obtains a solution parameterised on z and still faces a partial C&T constraint.

At the upper level, the policymaker's objective function is similar to that under PC (42) with an adjustment to the cost of damage from emissions to reflect that in (20). As in the PC case, we assume that the merchandising surplus accrues fully to an ISO based at node E:

$$\begin{aligned} \max_{z\geq 0} \quad & A_E\left(\hat{y}_E(z)+\hat{f}(z)\right)-\frac{1}{2}B_E\left(\hat{y}_E(z)+\hat{f}(z)\right)^2-C_E\hat{y}_E(z) \\ & -\hat{P_E}(z)\hat{f}(z)+(\hat{P_E}(z)-\hat{P_W}(z))\hat{f}(z)-\frac{1}{2}D\left(R_E\hat{y}_E(z)+R_W\hat{y}_W(z)\right)^2 \end{aligned} \tag{42}$$

We obtain the following first-order necessary condition to the QP in (42):

$$\begin{aligned} & A_E\hat{y}'_E(z)-B_E\left(\hat{y}_E(z)+K\right)\hat{y}'_E(z)-C_E\hat{y}'_E(z) \\ -&D\left(R_E\hat{y}_E(z)+R_W\hat{y}_W(z)\right)\left(R_E\hat{y}'_E(z)+R_W\hat{y}'_W(z)\right)=0 \end{aligned} \tag{43}$$

Solving, we obtain:

$$\tilde{z}=\frac{\left[R_EB_W\left(A_E-C_E-B_EK\right)-DR_WR_E^2\left(A_W-C_W+B_WK\right)\right]}{B_W\left(B_E+DR_E^2\right)} \tag{44}$$

Inserting $\tilde{z}$ into the lower-level parameterised solutions (30)–(33), we obtain:

$$\hat{\rho}(\tilde{z}) = D\frac{\left[B_WR_E\left(A_E-C_E-B_EK\right)+B_ER_W\left(A_W-C_W+B_WK\right)\right]}{B_W\left(B_E+DR_E^2\right)} \tag{45}$$

$$\hat{y}_E(\tilde{z}) = \frac{\left[B_W\left(A_E-C_E-B_EK\right)-DR_WR_E\left(A_W-C_W+B_WK\right)\right]}{B_W\left(B_E+DR_E^2\right)} \tag{46}$$

$$\hat{y}_W(\tilde{z}) = \frac{A_W-C_W+B_WK}{B_W} \tag{47}$$

$$\begin{aligned} \hat{\mu}^+(\tilde{z}) = \; & C_E-C_W \\ & +DR_E\frac{\left[B_WR_E\left(A_E-C_E-B_EK\right)+B_ER_W\left(A_W-C_W+B_WK\right)\right]}{B_W\left(B_E+DR_E^2\right)} \end{aligned} \tag{48}$$

The total emissions (including those at node W) under MC are:

$$R_E\hat{y}_E(\tilde{z})+R_W\hat{y}_W(\tilde{z}) = \frac{R_EB_W\left(A_E-C_E-B_EK\right)+R_WB_E\left(A_W-C_W+B_WK\right)}{B_W\left(B_E+DR_E^2\right)} \tag{49}$$

2.2.4. Import Coverage

In contrast to the MC model in Section 2.2.3, the policymaker at the upper level under IC selects the optimal emission cap considering node-E consumer surplus and producer surplus along with the cost of damage from emissions associated with the total quantity demanded at node E, i.e., emissions from domestic production and imports from node W. As under MC, the lower-level formulation and equilibrium are unchanged from Section 2.2.2, thereby resulting in the same lower-level solutions (30)–(33).

At the upper level, the objective function is slightly changed from that in (42) to replace total emissions at node W, $R_W y_W$, by imported emissions from node W, $R_W f$, in the final term:[6]

$$\begin{aligned}\max_{z\geq 0} \quad & A_E\left(\hat{y}_E(z)+\hat{f}(z)\right)-\frac{1}{2}B_E\left(\hat{y}_E(z)+\hat{f}(z)\right)^2-C_E\hat{y}_E(z)\\ & -\hat{P_E}(z)\hat{f}(z)+(\hat{P_E}(z)-\hat{P_W}(z))\hat{f}(z)-\frac{1}{2}D\left(R_E\hat{y}_E(z)+R_W\hat{f}(z)\right)^2\end{aligned} \tag{50}$$

As under MC, we obtain the following first-order necessary condition to the QP in (50):

$$\begin{aligned}& A_E\hat{y}_E'(z)-B_E\left(\hat{y}_E(z)+K\right)\hat{y}_E'(z)-C_E\hat{y}_E'(z)\\ & -D\left(R_E\hat{y}_E(z)+R_W K\right)R_E\hat{y}_E'(z)=0\end{aligned} \tag{51}$$

Solving, we obtain:

$$\underline{z}=\frac{R_E(A_E-B_EK-C_E-DR_ER_WK)}{B_E+DR_E^2} \tag{52}$$

Inserting $\underline{z}$ into the lower-level parameterised solutions (30)–(33), we obtain:

$$\hat{\rho}(\underline{z}) = \frac{D\left[R_E\left(A_E-C_E\right)+(R_W-R_E)B_EK\right]}{B_E+DR_E^2} \tag{53}$$

$$\hat{y}_E(\underline{z}) = \frac{A_E-B_EK-C_E-DR_ER_WK}{B_E+DR_E^2} \tag{54}$$

$$\hat{y}_W(\underline{z}) = \frac{A_W-C_W+B_WK}{B_W} \tag{55}$$

$$\hat{\mu}^+(\underline{z}) = -C_W+\frac{DR_E\left[R_E(A_E-B_EK)+R_WB_EK\right]+B_EC_E}{B_E+DR_E^2} \tag{56}$$

The total emissions (including those at node W) under IC are:

$$R_E\hat{y}_E(\underline{z})+R_W\hat{y}_W(\underline{z}) = \frac{R_EB_W\left(A_E-C_E-B_EK\right)+R_WB_E\left(A_W-C_W+B_WK\right)+DR_E^2R_W\left(A_W-C_W\right)}{B_W\left(B_E+DR_E^2\right)} \tag{57}$$

[6]The term $R_W\hat{f}(z)$ in (50) derives from the expression $max\{0,R_W\hat{f}(z)\}$; however, since we are interested only in interior solutions, we assume that $max\{0,R_W\hat{f}(z)\}=R_W\hat{f}(z)$.

2.3. Lower-Level Equilibrium Characterisation

In order to characterise equilibria and the basis for the interior solutions to the problems in Sections 2.2.1–2.2.4, we focus on the lower-level solutions to the full- and partial-coverage cases, (15)–(18) and (30)–(33), respectively, while holding z and K constant.[7] The corresponding linear relationship between z and K for each equation in each case is plotted in Figure 1 along with a label on the appropriate side of each line to ensure an interior solution. For each case, an interior solution is assured if all four lower-level variables are strictly positive, i.e., $\Omega^{FC} = \{\rho^*(z) > 0, y^*_E(z) > 0, y^*_W(z) > 0, \mu^{*,+}(z) > 0\}$ and $\Omega^{PC} = \{\hat{\rho}(z) > 0, \hat{y}_E(z) > 0, \hat{y}_W(z) > 0, \hat{\mu}^+(z) > 0\}$. Equivalently, z and K must be in the ranges sketched out by the corresponding lines for each case in order for each interior solution set to be non-empty. Moreover, the intersection between the two sets, $\Omega = \Omega^{FC} \cap \Omega^{PC}$, will be non-empty only if z and K are restricted as indicated by the shaded region in Figure 1.

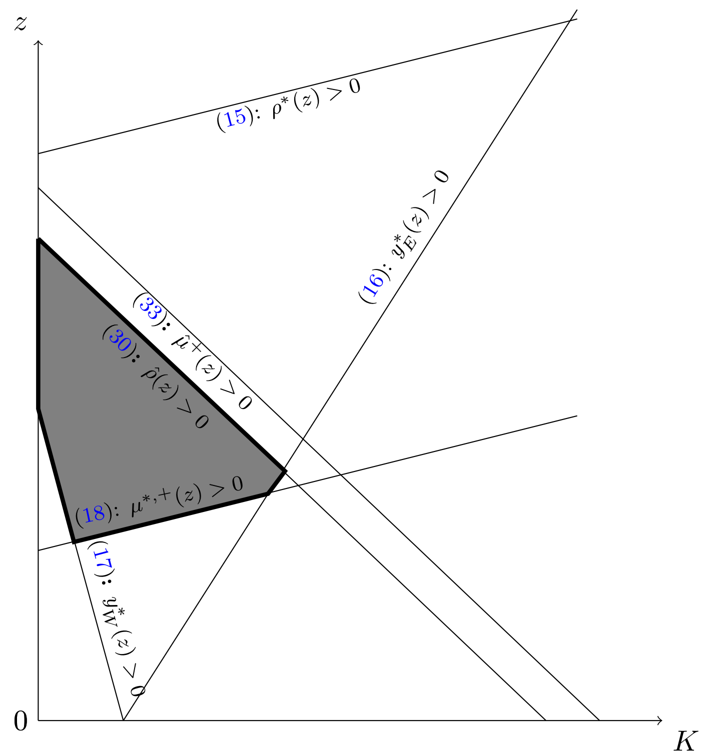

Figure 1: Characterisation of lower-level equilibria with respect to K and z

Intuitively, the FC interior solution set first establishes an upper bound on the emission limit, z, such that the C&T permit price is strictly positive (15). Indeed, if the emission limit is too lax, then it will be relatively easy to comply with, thereby causing the C&T permit price to crash to zero. Analogously, (15) establishes a lower limit on the size of the transmission line, K, below which relatively dirty production at node W will be minimal and obviate the need for a carbon

[7] Actually, the lower-level equilibria in the remaining cases are identical to those under PC, which is why we forego their characterisation.

policy. Next, (16) establishes an upper limit on K above which node-E generation will be zero as production from node W will satisfy all regional consumption. By the same token, (16) puts a floor on the emission limit as any tighter carbon policy will curb node-E production. Likewise, (17) puts a floor on the emission limit to ensure that node-W production is viable along with a minimum size for the transmission line. Finally, (18) puts a lower bound (an upper bound) on the emission limit (line capacity) below (above) which transmission capacity will not have marginal value.

The PC interior solution set can be characterised similarly: (30) and (33) establish upper bounds on z and K. However, the latter restriction is binding as long as the former one is, which means that (33) can be effectively disregarded. Likewise, (31) and (32) can be shown to be positive for any positive values of z and K. Focusing on (30), therefore, we note that while it is similar to the corresponding FC restriction in terms of establishing an upper limit on z, it actually requires an upper limit on K rather than a lower limit as under FC. The reason for this contrasting requirement has to do with the fact that the carbon policy applies only to node E under PC. Hence, if the transmission line is relatively large, then emissions will be under the limit z, thereby rendering a zero C&T permit price as node-E consumption will be heavily dependent on relatively dirty generation from node W that is exempt from the C&T permit price.

2.4. Comparative Statics

We analyse the impact of *ceteris paribus* changes in transmission capacity[8], K, and the cost of damage from emissions, D, on the emission cap, the C&T permit price, and the marginal value of transmission capacity. In particular, the latter serves as a proxy for potential carbon leakage under PC, MC, and IC as it reflects the propensity for expanding transmission capacity, which will attract more node-W imports to node E. Indeed, it represents the nodal price difference with a congested transmission line (or, equivalently, the marginal value of an infinitesimal increase in transmission capacity), and its realised value reflects the incentive of the transmission owner to expand capacity. Thus, through the following comparative statics, we formalise how alternative emission-coverage policies perform with respect to total emissions and the threat of carbon leakage. Following the exposition in Section 2.3, we assume that parameters are varied in a way to yield interior solutions, i.e., Ω is non-empty.

We explore how emission cap, permit price, and marginal value of transmission capacity are affected by the transmission capacity and the damage cost parameter. The variation of the emission cap, permit price, and marginal value of transmission capacity with parameters K and D is summarised in Table 1 where "+" ("-") means that the emission cap increases (decreases) with the parameter.

The impact of D on the emission cap, z, is intuitive as a policymaker would tighten the cap, z, in face of a larger D in the attempt to equalise the marginal damage with the permit price, ρ, thereby raising the permit price. The impact of D on the marginal value of transmission capacity,

[8] Since we conduct a *ceteris paribus* analysis with respect to transmission capacity, we do not consider the capital costs of expanding the transmission line in the social welfare calculation.

Table 1: Emission cap, permit price, and marginal value of transmission capacity changes with K and D

Variable	Parameter K	D
z^*	+	-
$\hat{z}$	-	-
$\tilde{z}$	-	-
$\underline{z}$	-	-
$\rho^*(z^*)$	+	+
$\hat{\rho}(\hat{z})$	-	+
$\hat{\rho}(\tilde{z})$	+	+
$\hat{\rho}(\underline{z})$	+	+
$\mu^{*,+}(z^*)$	-	-
$\hat{\mu}^+(\hat{z})$	-	+
$\hat{\mu}^+(\tilde{z})$	+	+
$\hat{\mu}^+(\underline{z})$	+	+

μ^+, a proxy for the leakage potential, is aligned with the impact on the permit price, ρ, except for the FC policy. Under PC, MC, and IC, a change in ρ will impact only the power price at node E, whereas the power price at node W will be equal to C_W since node W is not under the C&T. In turn, this will be reflected in the power price differential, μ^+. Under FC, when emissions from both nodes E and W are covered by the cap, the power price at node W will increase by more than that at node E due to node W's higher emission rate. Thus, the price differential between the two nodes will shrink leading to a reduction in the marginal value of transmission capacity.

The impact of transmission capacity, K, on the emission cap, z, depends on the emissions considered damaging by the policymaker at the upper level. Under all policies, an increase in K causes clean production at node E to be replaced by dirty production at node W. Under FC, since node-W emissions are covered by the cap, raising the emission cap, z, is necessary to equate the marginal damage cost of emissions with the permit price. The contrary is true for PC, MC, and IC where only emissions from node E are covered by the cap. Consequently, an increase in K lowers "local" emissions. If emissions from node W are included in the policymaker's problem either directly (FC) or indirectly (MC and IC), then the policymaker adjusts the cap so that it raises the permit price in the attempt to equalise the marginal damage of increased dirtier production. On the other hand, when node-W emissions are not included in the policymaker's problem (PC), the increase in imports from node W suppresses the demand for the permits due to lower emissions at node E, which leads to a drop in the permit price.

Proposition 1. *Impact of D and K on z.*

(i) Under FC, total emissions, z^*, increase (decrease) due to a ceteris paribus *increase in the transmission capacity, K (in the damage cost parameter, D).*

(ii) Under PC, MC, and IC, the node-E emission cap, $\hat{z}$, $\tilde{z}$, and $\underline{z}$, respectively, decreases due to a ceteris paribus *increase in either the transmission capacity, K, or the damage parameter, D.*

Both findings under Proposition 1(i) are generally intuitive: a larger transmission line increases total emissions because more node-W generation is able to meet node-E consumption. Conversely, a higher cost of damage parameter stifles consumption, thereby reducing generation in proportion to its emission rate and subsequently reducing overall emissions. The impact of the damage cost parameter on the emission cap in Proposition 1(ii) is similar to that under FC. Unlike the FC result, the policymaker under PC, MC, and IC actually tightens the emission cap, which applies only to node-E generation, if the transmission capacity increases. Concerned about only node-E welfare and emissions, the policymaker is unable to trade off the system-wide benefits and costs of the larger transmission line. Thus, it attempts to curtail relatively clean generation at node E via a more stringent emission cap, which may exacerbate not only total emissions but also carbon leakage. This latter aspect can be formalised via the following result where we investigate how the marginal value of transmission capacity is affected by the transmission capacity and the damage cost parameter:

Proposition 2. *Impact of D and K on μ^+.*

(i) Under FC, the marginal value of transmission capacity, $\mu^{*,+}$, decreases due to a ceteris paribus *increase in either the transmission capacity, K, or the damage cost parameter, D.*

(ii) Under PC, the marginal value of transmission capacity, $\hat{\mu}^+(\hat{z})$, decreases (increases) due to a ceteris paribus *increase in the transmission capacity, K (in the damage cost parameter, D).*

(iii) Under MC and IC, the marginal value of transmission capacity, $\hat{\mu}^+(\tilde{z})$ and $\hat{\mu}^+(\underline{z})$, increases due to a ceteris paribus *increase in either the transmission capacity, K, or the damage cost parameter, D.*

Proposition 2(i)'s findings are generally intuitive: the transmission line has a lower marginal value the larger its capacity becomes, while a larger damage cost D will curb node-W production, resulting in less exports to node E. These comparative statics may also be visualised in Figures 2 and 3 as a high K (low z or high D) will decrease $\mu^{*,+}$. In relation to Proposition 3(i), since node W is not impacted by carbon policy, its equilibrium power price under PC will be lower than that under FC. Moreover, the equilibrium power price at node E will tend to be higher under PC as it bears the brunt of a tighter emission cap. Consequently, the higher nodal price difference leads to a higher marginal value of transmission capacity and potential for carbon leakage. Also in contrast to the FC result, the marginal value of transmission capacity under PC actually increases with the damage cost parameter D (Proposition 2(ii)). Specifically, by setting an emission cap only for node E, the policymaker enlarges the nodal price difference when facing an increased damage cost D by reducing its optimal emission cap $\hat{z}$, thereby worsening emission leakage.

Proposition 3. *Comparison of μ^+ across policies.*

(i) Under PC, the marginal value of transmission capacity, $\hat{\mu}(\hat{z}^+)$ is higher than that under FC, $\mu^{*,+}(z^*)$.

(ii) Under MC, the marginal value of transmission capacity, $\hat{\mu}^{+}(\tilde{z})$, is higher than that under both FC, $\mu^{*,+}(z^{*})$, and PC, $\hat{\mu}^{+}(\hat{z})$.

(iii) Under IC, the marginal value of transmission capacity, $\hat{\mu}^{+}(\underline{z})$, is lower than that under MC, $\hat{\mu}^{+}(\tilde{z})$, and greater than that under PC, $\hat{\mu}^{+}(\hat{z})$.

According to Proposition 3(ii), due to a tighter node-E cap under MC (see Proposition 4(i)), the marginal value of transmission capacity under MC is greater than that under FC and PC. Moreover, as shown in Proposition 2(iii), although the marginal value of transmission capacity under MC increases with the damage cost parameter as under PC (but in contrast to FC), it actually increases with the transmission capacity (in contrast to both FC and PC). The explanation for the increase in $\hat{\mu}^{+}(\tilde{z})$ with respect to D is similar to that under PC, i.e., a tighter node-E cap only exacerbates the nodal price difference and enhances the prospect of carbon leakage. This attribute is especially striking when considering the positive impact of K on $\hat{\mu}^{+}(\tilde{z})$. Indeed, unlike the conventional behaviour of shadow prices that decrease with capacity, here, the attempt by the policymaker at node E to internalise the cost of damage from emissions at node E via a tighter emission cap more than offsets the (direct) effect of a higher capacity on the shadow price of transmission. Hence, although total regional emissions are lower under MC relative to PC, the potential for carbon leakage is increased.

As shown in Proposition 3(iii), since the node-E emission cap is looser (tighter) under IC compared to MC (PC) according to Proposition 4(ii), the marginal value of transmission capacity under IC is lower (greater) than that under MC (PC). Thus, IC alleviates the potential for carbon leakage, albeit at the cost of higher total regional emissions relative to MC. Furthermore, although the marginal value of transmission capacity still increases with respect to the transmission capacity and the damage cost parameter (as under MC) (see Proposition 2(iii)), its rate of increase with respect to D is lower than under MC.

Proposition 4. *Comparison of z across policies.*

(i) Under MC, both the node-E emission cap, $\tilde{z}$, and the total system emissions are lower than those under PC.

(ii) Under IC, both the node-E emission cap, $\underline{z}$, and the total system emissions are higher (lower) than those under MC (PC).

As shown in Proposition 4(i), accounting for node-W emissions leads the policymaker to set a tighter cap in MC than in PC, and thus, obtain lower total emissions with the former. In comparing IC with PC and MC, we find that including only the imported node-W emissions on top of the node-E emissions leads the policymaker to set a looser cap and to obtain higher total emissions in comparison to MC but still lower than those under PC (see Proposition 4(ii)).

Proposition 5. *Impact of D and K on ρ.*

(i) Under FC, MC, and IC, the C&T permit price, $\rho^*(z^*)$, $\hat{\rho}(\tilde{z})$, and $\hat{\rho}(\underline{z})$, respectively, increases due to a ceteris paribus *increase in either the transmission capacity, K, or the damage cost parameter, D.*

(ii) Under PC, the C&T permit price, $\hat{\rho}(\hat{z})$, decreases (increases) due to a ceteris paribus *increase in the transmission capacity, K (in the damage cost parameter, D).*

Following a similar logic as in the case of marginal value of transmission, the C&T permit price under FC can be shown to be increasing with both the transmission capacity and the damage cost parameter (see Proposition 5(i)). First, a higher transmission capacity enables more node-W production to meet consumption at node E, thereby giving the price signal for consumption to be curbed. Second, a higher damage cost parameter tightens the emission cap, which makes C&T permits more scarce. Although the C&T permit price under PC still increases due to a higher damage cost as under FC, the finding with respect to the transmission capacity is reversed as shown in Proposition 5(ii). Intuitively, a larger line displaces node-E production with node-W production, which is exempt from the emission cap. Thus, even though the node-E emission cap tightens as the transmission capacity increases, which should increase the C&T permit price, it is more than offset by the influx of additional node-W imports. Hence, node E has lower local emissions, thereby causing the C&T permit price to crash.

In a similar vein to the marginal value of transmission, the C&T price under MC and IC increases with respect to the damage cost parameter to an even greater extent than under PC but increases with respect to the capacity of the transmission line (as under FC but in contrast to PC) as the emission cap tightens to a greater extent.

3. Numerical Examples

Numerical examples are presented in this section using data in Table 2 in order to illustrate our findings in Section 2. Except for allowing D and K to change within the interior solution set, Ω, as sketched in Figure 1, data in Table 2 are fixed in our analyses. More specifically, we vary parameters D and K within respective intervals of $[0, 0.26]$ and $[1, 110]$ in order to examine how the marginal value of transmission capacity, μ^+, the price of C&T permits, ρ, the cap on emissions, z, total emissions in the system, and social welfare as defined in (19) are impacted.[9]

According to Proposition 2, as the emission cap internalises the increasing damage from emissions D, the incentive to increase the capacity of the line decreases in the case of FC and increases in all other coverage policies (Figure 2). Moreover, as indicated in Proposition 3(i), the incentive under PC is higher than that under FC due to the fact that production at node W is not directly curbed by the carbon policy. Furthermore, the incentive to expand the line increases due to the

[9]The intervals for D and K are selected to avoid economically uninteresting solutions in which the optimal emission cap is zero for any coverage policy. For example, Figures 6 and 7 indicate that the optimal emission cap goes to zero under MC for $D = 0.26$ and $K = 110$, respectively. As for the lower limit on K, we choose 1 in order to avoid trivial solutions with disconnected nodes.

Table 2: Data for numerical examples

Parameter	Value
A_E	200
A_W	150
B_E	1
B_W	1
C_E	80
C_W	20
R_E	1
R_W	1.8

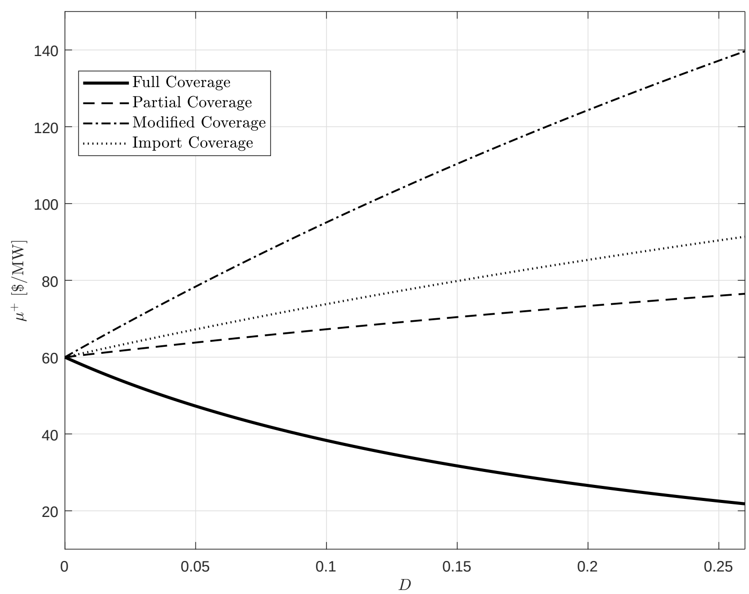

Figure 2: Impact of the damage cost parameter on the marginal value of transmission capacity

tightening cap that induces a higher price at node E that, in turn, entices node-W production. This incentive grows further under MC (see Proposition 3(ii)) as the cap is tightened by including damage from emissions from node W, thus, setting the cap by considering damage from both nodes while imposing the policy only over node E. This effect is alleviated when we internalise only the damage from emissions associated with imports from node W (see Proposition 3(iii)) rather than all the emissions from node W.

In agreement with Proposition 2, the incentive to expand the line decreases with larger line capacity under FC and PC (Figure 3). Furthermore, as identified in Proposition 3(i), the incentive is higher under PC due to the exemption of node-W producers from the C&T. The incentive grows even further as a tighter cap is imposed on node E under MC. As shown in Proposition 2(iii), under MC, a larger line actually increases the incentive to increase the line capacity further.

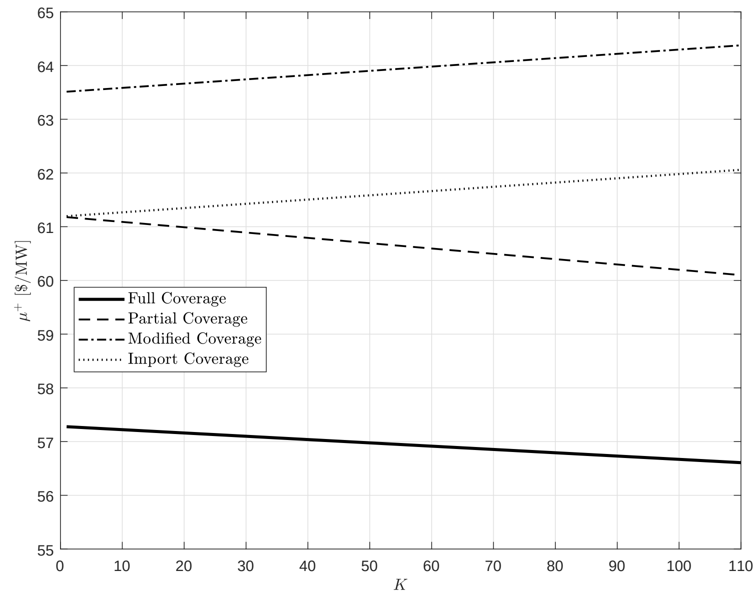

Figure 3: Impact of the transmission capacity on the marginal value of transmission capacity

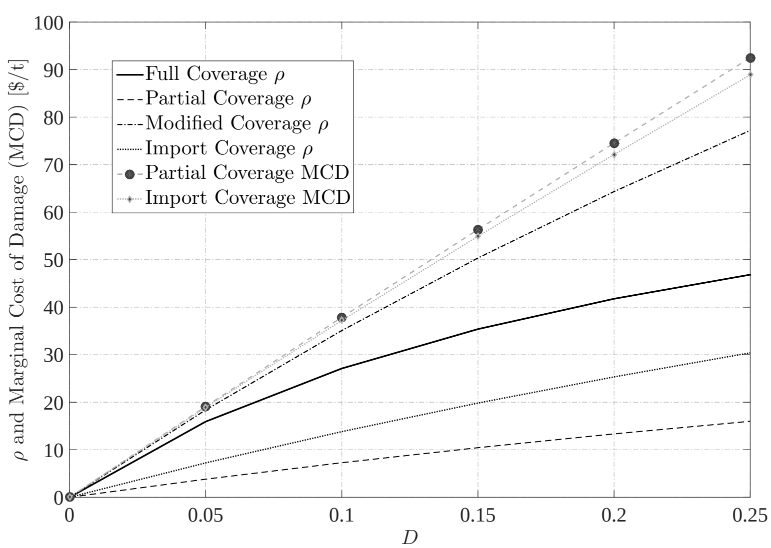

Figure 4: Impact of the damage cost parameter on the C&T price

As the damage cost parameter increases, so does the C&T price in the policymaker's attempt of equalising it with the marginal cost of damage and in order to curb production while keeping in mind the indirect effect of doing so, i.e., higher electricity prices that could induce an increase in production (Figure 4). This effect occurs under all policies as indicated in Proposition 5; however, only under FC and MC is the policymaker able to equalise the permit price with the marginal cost of damage as these are the only two policies where total emissions in the system are taken into account by the policymaker. The C&T price is lower under PC compared to the one under FC due to the smaller size of the C&T. Under MC, however, due to a more stringent cap over the same market size (see Proposition 4(i)), the C&T price is higher than under PC. The C&T price under IC drops to levels closer to the price under PC because of the less stringent cap compared to the one under MC (see Proposition 4(ii)).

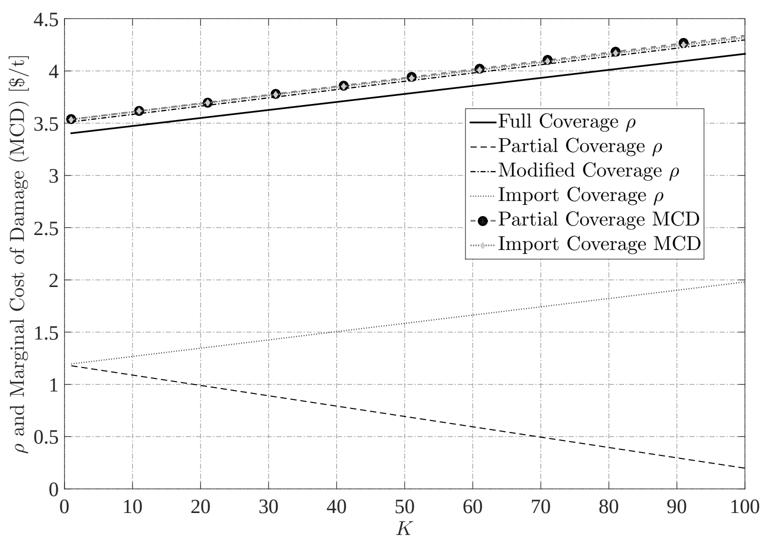

Figure 5: Impact of the transmission capacity on the C&T price

According to Proposition 5(i), as the line increases, a higher C&T price is required to deter more-polluting imports from node W under FC (Figure 5). Not only is the C&T price lower under PC due to the smaller size of the C&T, but also the C&T price decreases with a larger line as more production is displaced from node E to node W (see Proposition 5(ii)). In fact, PC is the only policy in which the price of permits actually diverges from the marginal cost of damage as K increases. The C&T price is higher under MC compared to the one under FC as it imposes a tighter cap on a smaller size of C&T. In line with Proposition 5(i), the C&T price is increasing with a larger line as it tries to compensate for increased emissions at node W. IC presents a compromise between MC and PC as the C&T price is lower than under MC, but, in contrast to PC (see Proposition 5(i)), the C&T price is increasing with a larger line, thus, trying to curb emissions in the system.

Figures 6 and 7 indicate the impact of the damage cost parameter and the transmission capacity on the optimal carbon policy, respectively. As seen in Proposition 1, while the cap becomes tighter under all policies as the former increases, only under FC does the cap loosen as the transmission

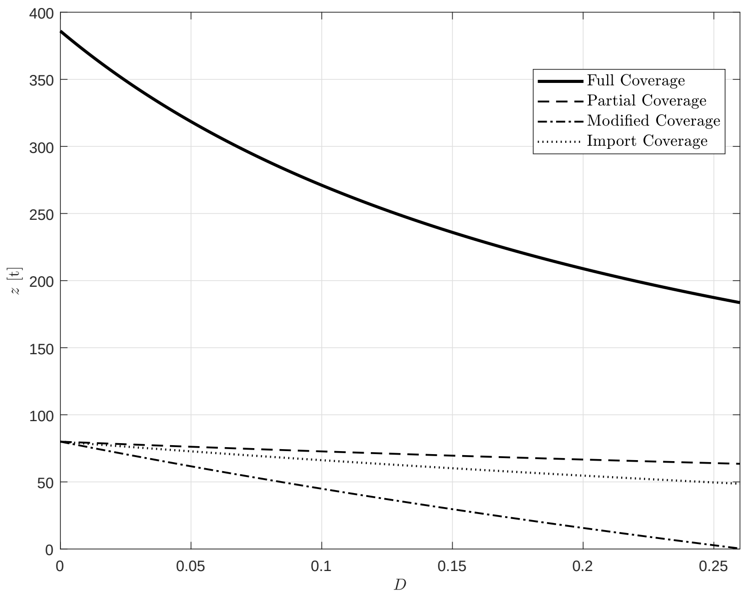

Figure 6: Impact of the damage cost parameter on the node-E cap (cap for both nodes under FC)

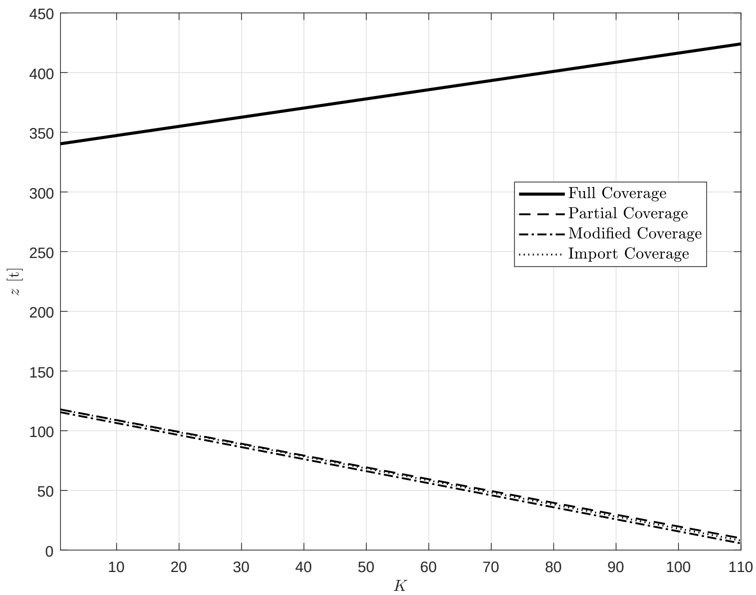

Figure 7: Impact of the transmission capacity on the node-E cap (cap for both nodes under FC)

capacity increases. Figures 8 and 9 illustrate the intuitive findings that total emissions decrease (increase) with the damage cost parameter (transmission capacity). As noted with reference to carbon leakage, IC is a compromise between PC and MC also in terms of total emissions. Likewise, Figures 10 and Table 3 present similar findings and insights with respect to the total social welfare in the region.

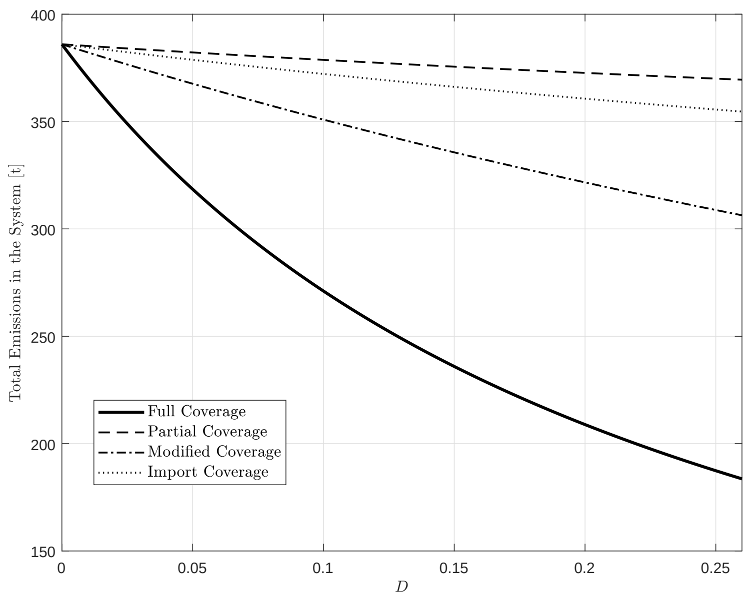

Figure 8: Impact of the damage cost parameter on total emissions

Table 3: Impact of transmission capacity K on social welfare [$] across policies

Policy \ K [MW]	25	50	75	100
Full Coverage	16,479	17,905	19,327	20,746
Partial Coverage	16,453	17,876	19,294	20,709
Modified Coverage	16,457	17,881	19,301	20,717
Import Coverage	16,454	17,878	19,298	20,714

4. Conclusion and Policy Implications

Given the stipulations of the Paris Agreement, a variety of carbon policies implemented around the world will likely remain in effect in the foreseeable future. One concern is that polices with different stringencies might result in so-called carbon leakage, where pollution from emissions in a region with less-stringent policy might increase in response to a more-stringent policy implemented by the neighbouring region. Regional electricity markets are particularly susceptible to carbon leakage due to the dependency of regions with capped emissions on imports from uncapped regions, e.g., California EIM and PJM. Since carbon leakage can have a detrimental effect on emission-reduction

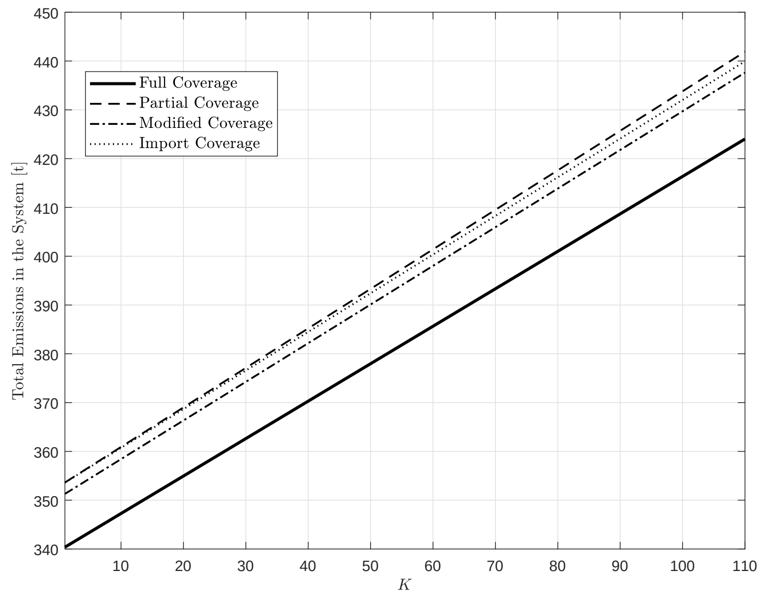

Figure 9: Impact of the transmission capacity on total emissions

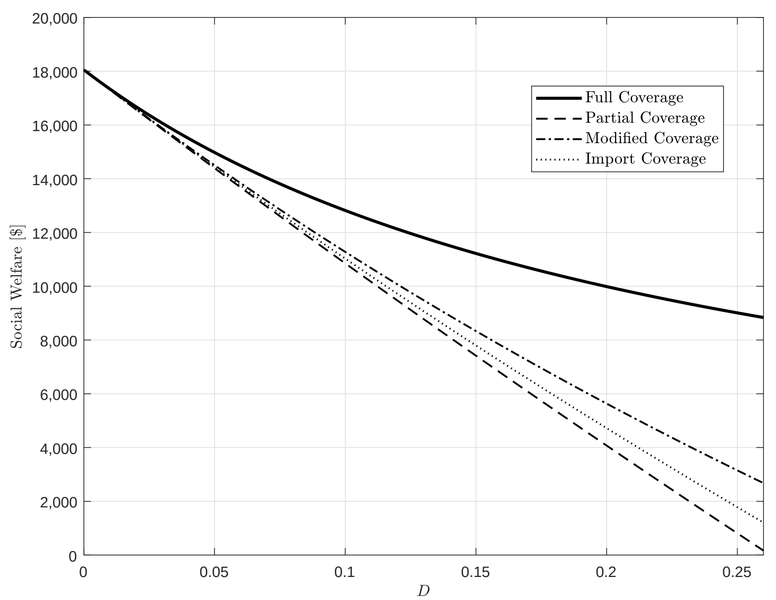

Figure 10: Impact of the damage cost parameter on social welfare

targets, this calls for implementation of corrective measures for carbon-leakage mitigation. Several measures such as carbon tariffs, free allowance allocation, and mandatory purchase of permits for emissions from goods imported from an unregulated area have been proposed, but each of these faces some limitations.

We develop an analytical bi-level model in which we use a C&T cap in a regional electricity market as a remedy for carbon leakage. Specifically, we consider a policymaker whose goal is to set an optimal emission cap for the node in its jurisdiction, which depends on imports from an unregulated node. Despite the limited reach of its jurisdiction, the policymaker is aware that damage from CO_2 emissions, regardless of its origin, affects regional welfare. This leads to the question: which emissions should the policymaker consider damaging when setting the cap, keeping in mind that it cannot force producers at the unregulated node to comply with the C&T?

For the purpose of answering this question, we propose three coverage policies, viz., partial-, modified-, and import-coverage, and compare these to the full-coverage policy representing the first-best solution. We find that partial coverage, which is comparable to the conventional source-based regulation, leads to a shadow price on transmission capacity higher than that under full coverage due to the price differential driven by the price of permits at the regulated node. Consequently, unregulated producers are perversely incentivised to export to the regulated area, thereby resulting in a greater potential for carbon leakage. Somewhat surprisingly, the potential for carbon leakage is further exacerbated as the price differential widens when the cap is set considering damage from total emissions in the system. A middle ground for mitigating carbon leakage is the import coverage; however, this welfare-decreasing policy leads to higher total CO_2 emissions compared to modified coverage. This is mainly because the policymaker implements a looser cap under import coverage compared to modified coverage as only emissions from imports to the regulated node are considered to be damaging. In conclusion, we find that the import-coverage policy, broadly consistent with the one used in California, is a potential way forward due to its lower potential for carbon leakage compared to the modified-coverage policy and broader scope compared to the partial-coverage policy.

Implementation of partial-, modified-, or import-coverage policies could be subject to critiques applied to carbon tariffs as they might be politically or legally challenging to implement. For example, the industry at the regulated node under the modified-coverage policy could be opposed to paying for the cost of emissions generated elsewhere. In addition, the policies analysed might face similar difficulties as the one implemented in California, viz., determining the emission rate of the unregulated region. For example, the EU estimates the carbon footprint of goods imported into the EU based on emission intensities of the EU's domestic production processes (Eurostat, 2018).

In this paper, carbon leakage is limited by the maximum capacity of the transmission line connecting the regulated and non-regulated subregions of the regional power market. However, carbon leakage can also be limited by the installed capacity in the non-regulated subregion. This aspect is beyond the scope of our analysis, but it would be relevant to include it in future research in order to understand the interaction between the transmission line and the non-regulated subregion generation capacity. Furthermore, since the analysis in this paper suggests that carbon leakage could be exacerbated by a larger transmission line capacity under some policies, it would be pertinent to introduce multiple operational periods and uncertainty that would allow for a long-term analysis involving capacity investment in both generation and transmission (Conejo et al., 2016; Strand et al., 2014).

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Appendix: Proofs of Propositions

Proof of Proposition 1(i)

The result follows from partial differentiation of (22) with respect to either K or D:

$$\frac{\partial z^*}{\partial K} = \frac{\left(R_W - R_E\right) B_E B_W}{B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)} > 0$$
$$\frac{\partial z^*}{\partial D} = -\frac{\left(R_W^2 B_E + R_E^2 B_W\right)\left[B_E R_W \left(A_W - C_W + B_W K\right) + B_W R_E \left(A_E - C_E - B_E K\right)\right]}{\left[B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)\right]^2} < 0$$

□

Proofs of Proposition 1(ii)

The result follows from partial differentiation of (36) with respect to either K or D:

$$\frac{\partial \hat{z}}{\partial K} = -\frac{B_E R_E}{B_E + D R_E^2} < 0$$
$$\frac{\partial \hat{z}}{\partial D} = -R_E^2 \frac{R_E\left(A_E - C_E - B_E K\right)}{\left(B_E + D R_E^2\right)^2} < 0$$

□

The result follows from partial differentiation of (44) with respect to either K or D:

$$\frac{\partial \tilde{z}}{\partial K} = -\frac{R_E\left(B_E + DR_W R_E\right)}{B_E + DR_E^2} < 0$$
$$\frac{\partial \tilde{z}}{\partial D} = -R_E^2 \frac{\left[B_W R_E\left(A_E - C_E - B_E K\right) + B_E R_W\left(A_W - C_W + B_W K\right)\right]}{B_W\left(B_E + DR_E^2\right)^2} < 0$$

□

The result follows from partial differentiation of (52) with respect to either K or D:

$$\frac{\partial \underline{z}}{\partial K} = -\frac{R_E(B_E + DR_E R_W)}{B_E + DR_E^2} < 0$$
$$\frac{\partial \underline{z}}{\partial D} = -R_E^2 \frac{R_E\left(A_E - C_E - B_E K\right) + B_E R_W K}{\left(B_E + DR_E^2\right)^2} < 0$$

□

Proof of Proposition 2(i)

The result follows from partial differentiation of (26) with respect to either K or D evaluated at z^*:

$$\frac{\partial \mu^{*,+}(z^*)}{\partial K} = -\frac{D\left(R_W - R_E\right)^2 B_E B_W}{B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)} < 0$$
$$\frac{\partial \mu^{*,+}(z^*)}{\partial D} = -\frac{\left(R_W - R_E\right) B_E B_W\left[B_E R_W\left(A_W - C_W + B_W K\right) + B_W R_E\left(A_E - C_E - B_E K\right)\right]}{\left[B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)\right]^2} < 0$$

□

Proof of Proposition 2(ii)

The result follows from partial differentiation of (40) with respect to either K or D evaluated at $\hat{z}$:

$$\frac{\partial \hat{\mu}^+(\hat{z})}{\partial K} = -\frac{B_E DR_E^2}{B_E + DR_E^2} < 0$$
$$\frac{\partial \hat{\mu}^+(\hat{z})}{\partial D} = \frac{B_E R_E^2\left(A_E - C_E - B_E K\right)}{\left(B_E + DR_E^2\right)^2} > 0$$

□

Proofs of Proposition 2(iii)

The result follows from partial differentiation of (48) with respect to either K or D evaluated at $\tilde{z}$:

$$\frac{\partial \hat{\mu}^+(\tilde{z})}{\partial K} = \frac{B_E DR_E\left(R_W - R_E\right)}{B_E + DR_E^2} > 0$$
$$\frac{\partial \hat{\mu}^+(\tilde{z})}{\partial D} = B_E R_E \frac{\left[B_W R_E\left(A_E - C_E - B_E K\right) + B_E R_W\left(A_W - C_W + B_W K\right)\right]}{B_W\left(B_E + DR_E^2\right)^2} > 0$$

□

The result follows from partial differentiation of (56) with respect to either K or D evaluated at $\underline{z}$:

$$\frac{\partial \hat{\mu}^{+}(\underline{z})}{\partial K} = \frac{DR_E B_E \left[R_W - R_E\right]}{B_E + DR_E^2} > 0$$
$$\frac{\partial \hat{\mu}^{+}(\underline{z})}{\partial D} = \frac{R_E B_E \left[R_E(A_E - B_E K - C_E) + B_E R_W K\right]}{\left(B_E + DR_E^2\right)^2} > 0$$

□

Proof of Proposition 3(i)

We compare (40) with (26):

$$\hat{\mu}^{+}(\hat{z}) > \mu^{*,+}(z^*)$$
$$\Rightarrow \frac{DR_E^2 \left(A_E - C_E - B_E K\right)}{B_E + DR_E^2}$$
$$> -\frac{D\left(R_W - R_E\right)\left[B_E R_W \left(A_W - C_W + B_W K\right) + B_W R_E \left(A_E - C_E - B_E K\right)\right]}{B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)}$$

Since the left-hand side is always positive and the right-hand side is always negative, the result follows. □

Proof of Proposition 3(ii)

We compare (48) with (40):

$$\hat{\mu}^{+}(\tilde{z}) > \hat{\mu}^{+}(\hat{z})$$
$$\Rightarrow \frac{DR_E^2 \left(A_E - C_E - B_E K\right)}{B_E + DR_E^2} + \frac{DR_E R_W B_E \left(A_W - C_W + B_W K\right)}{B_W \left(B_E + DR_E^2\right)}$$
$$> \frac{DR_E^2 \left(A_E - C_E - B_E K\right)}{B_E + DR_E^2}$$

Since the left-hand side is greater than the right-hand side, the result follows. □

Proofs of Proposition 3(iii)

We first compare (56) with (48):

$$\hat{\mu}^{+}(\underline{z}) < \hat{\mu}^{+}(\tilde{z})$$
$$\Rightarrow 0 < A_W - C_W$$

Since the right-hand side is positive by assumption, the result follows. Next, we compare (56) with

(40):

$$\hat{\mu}^{+}(\underline{z}) > \hat{\mu}^{+}(\hat{z})$$
$$\Rightarrow D R_E R_W B_E K > 0$$

Again, the result follows because K is assumed to be positive. □

Proof of Proposition 4(i)

The result follows by comparing (44) with (36) and (49) with (41), respectively. □

Proof of Proposition 4(ii)

The results follow by comparing either (52) with (44) and (57) with (49) or (52) with (36) and (57) with (41). □

Proofs of Proposition 5(i)

The result follows from partial differentiation of (23) with respect to either K or D evaluated at z^*:

$$\frac{\partial \rho^*(z^*)}{\partial K} = \frac{D\left(R_W - R_E\right) B_E B_W}{B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)} > 0$$
$$\frac{\partial \rho^*(z^*)}{\partial D} = \frac{B_E B_W\left[B_E R_W\left(A_W - C_W + B_W K\right) + B_W R_E\left(A_E - C_E - B_E K\right)\right]}{\left[B_E B_W + D\left(R_W^2 B_E + R_E^2 B_W\right)\right]^2} > 0$$

□

The result follows from partial differentiation of (45) with respect to either K or D evaluated at $\tilde{z}$:

$$\frac{\partial \hat{\rho}(\tilde{z})}{\partial K} = \frac{D B_E\left(R_W - R_E\right)}{B_E + D R_E^2} > 0$$
$$\frac{\partial \hat{\rho}(\tilde{z})}{\partial D} = B_E \frac{\left[B_W R_E\left(A_E - C_E - B_E K\right) + B_E R_W\left(A_W - C_W + B_W K\right)\right]}{B_W\left(B_E + D R_E^2\right)^2} > 0$$

□

The result follows from partial differentiation of (53) with respect to either K or D evaluated at $\underline{z}$:

$$\frac{\partial \hat{\rho}(\underline{z})}{\partial K} = \frac{D\left(R_W - R_E\right) B_E}{B_E + D R_E^2} > 0$$
$$\frac{\partial \hat{\rho}(\underline{z})}{\partial D} = \frac{B_E\left[R_E(A_E - C_E) + (R_W - R_E) B_E K\right]}{\left(B_E + D R_E^2\right)^2} > 0$$

□

Proof of Proposition 5(ii)

The result follows from partial differentiation of (37) with respect to either K or D evaluated at $\hat{z}$:

$$\frac{\partial\hat{\rho}(\hat{z})}{\partial K} = -\frac{DR_E B_E}{B_E + DR_E^2} < 0$$
$$\frac{\partial\hat{\rho}(\hat{z})}{\partial D} = \frac{B_E R_E \left(A_E - C_E - B_E K\right)}{\left(B_E + DR_E^2\right)^2} > 0$$

□