Climate policy and electricity trade

Stefan Ambec[*] Yuting Yang[†]

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Abstract

The lack of coordinated international climate policies raises leakage concerns in the design of energy transition policies. We investigate the optimal unilateral carbon policy design for electricity trade with intermittent renewable energy. We consider policy instruments including carbon tax, border adjustment tax, and renewable subsidies. In turn, we analyze the effect of such policies on market equilibrium prices, renewable investment, and global emissions. Using a two-country model of electricity trade, we characterize the conditions under which different combinations of policy instruments implement the optimal energy mix. We find that with a unilateral carbon tax, the border adjustment tax turns out to be effective only when renewables are producing. Moreover, renewables must be subsidized to be exported, in which case carbon emissions should be taxed more than the Pigouvian level to avoid excessive consumption.

Keywords: Intermittent renewables, electricity interconnection, carbon tax, border adjustment tax, renewable subsidy, carbon leakage.

JEL Classification: D24, F18, F64, H23, Q27, Q48, Q54

[*]Toulouse School of Economics. Email: stefan.ambec@tse-fr.eu
[†]Toulouse School of Economics. Email: yuting.yang@tse-fr.eu

1 Introduction

Electricity interconnection has been promoted in many countries as a means to increase energy efficiency and security, and to facilitate renewable diffusion to areas lacking the technology or natural resources.[1] It is indeed a viable solution against renewable intermittency and to mitigate carbon emissions provided that the interconnected countries have coordinated carbon policies at the appropriate level (Yang 2020). However, most countries or regions do not adopt homogeneous carbon policies.[2] For example, California has a stringent cap-and-trade policy program, but its interconnected states in the western United States do not have any carbon policies in place. Prete et al. (2019) estimate a leakage rate of 70% with the unilateral carbon policy in California.

In this paper, we examine the optimal climate policy when electricity is traded across jurisdictions (countries or federal States). More precisely, we investigate how a jurisdiction should design its policy to reduce carbon emissions from electricity provision when its trading partner to not regulate their emissions. Electricity trade has some benefits, such as giving access to cheaper electricity or more diversified sources of energy. It also allows a country that supports renewables to export green electricity. However, by opening to trade, a country does not control the carbon emitted by electricity produced abroad including the one it imports. The trade induced competition may then crowd out the renewable investment in the region with a carbon policy. Moreover, renewable intermittency brings new concerns for policymaking, because of the weather-dependent trade flow. Ignoring intermittency may overlook some of the effective policies.

We consider a combination of policy instruments including a carbon tax, a border adjustment tax, and renewable subsidies. We analyze how the policies affect electricity market prices, renewable capacity investment, and global emissions with a two-countries model of electricity production and consumption with electricity trade, where one country adopts a unilateral carbon policy. The electricity markets are integrated up to the exogenously given transmission capacity limit. The government which cares about climate chooses the policy that maximizes the country's welfare net of climate damage given the available instruments.

With this framework, we first characterize the efficient energy mix when a social planner maximizes the joint welfare in both regions. This serves as the benchmark case for the

[1]For example, the European Union (EU) has set out a policy target to expand the electricity interconnection capacity between its member countries (European Commission 2018). MacDonald et al. (2016) simulate that a national grid system in the United States has the potential to reduce by up to 80% of its carbon dioxide emissions relative to 1990 levels.

[2]The exception being the EU, where member countries are under the same Emissions Trading System (EU-ETS).

comparative statics analysis. It would also be the energy mix that the country who cares about climate would implement if it could tax climate emissions abroad. Next, we examine the optimal tax rate if the country can only implement a unilateral carbon tax. In turn, we obtain the equilibrium energy mix and emissions level given the carbon tax. We find that the optimal tax level is equal to the marginal environmental damage if the transmission constraint is binding. With a non-binding transmission constraint, a carbon tax is not effective at any level. Moreover, the carbon tax alone is sufficient in obtaining the optimal energy mix in the country implementing the tax only when the marginal emissions damage is low. It would lead to under-investment in renewable capacity at a high marginal damage.

We then introduce border adjustment tax as an additional policy instrument on top of the carbon tax. Border tax increases import prices of thermal electricity, therefore avoids the crowding out of local renewable capacity. However, it cannot induce additional renewable capacity to be built for export. Moreover, as the two countries become more integrated, border tax is especially important to limit excess consumption of electricity.

We also analyze the effectiveness of recycling the tax revenue in the form of a renewable subsidy. We separately consider subsidizing domestic or foreign renewable capacity. A domestic subsidy can incentivize more renewable capacity for export. However, its effectiveness is bounded by the transmission capacity. Moreover, a higher than the Pigouvian level of carbon tax needs to be implemented to limit domestic consumption from thermal power, which would also increase emissions. An international subsidy, on the other hand, helps to relax the transmission constraint. An international subsidy can further reduce carbon leakage and increase renewable investment. Given the contentious border tax, which can result in regional policy disputes, we purpose that recycling the carbon and border tax revenue as an international renewable subsidy can be a win-win solution for all.

This paper is closely related to two strands of literature. First is the literature on the optimal provision of electricity with intermittent renewable energy. A growing literature studies how the intermittency of renewable energy affects the optimal energy mix and market equilibrium in the electricity market. Ambec and Crampes (2012) construct a model that characterizes the optimal energy mix between the reliable source and the intermittent source and analyze the market structure to decentralize the optimal mix. The literature also analyzes issues including how different policy instruments, demand-side response, and storage technology affect the optimal energy mix with renewable intermittency (Ambec and Crampes 2019; Helm and Mier 2019). Yang (2020) extends their framework to consider two countries and analyze how electricity interconnections affect the optimal energy mix in the two countries. She finds that even with coordinated carbon policies, electricity interconnection can lead to increased carbon emissions depending on the energy source available in the interconnected countries. In contrast, we consider unilateral carbon policies and examine the second-best policy bundle when there is electricity interconnection.

This paper also contributes to the literature on unilateral carbon policy and carbon leakage. Both theoretical analyses and empirical evidence have shown that a unilateral carbon policy may lead to the relocation of firms due to the loss of competitiveness in the region. Consequently, the firms will emit outside of the policy jurisdiction, which is referred to as carbon leakage. To address this leakage issue, the literature discusses several policy instruments, including border carbon adjustment tax, export rebate, allocation of free emission permits, along with emission pricing (Böhringer, Bye, et al. 2017; Böhringer, Fischer, et al. 2014; Böhringer, Rosendahl, et al. 2017; Dissou and Eyland 2011; Fischer and Fox 2012; Markusen 1975; Martin et al. 2014). Our analysis focus on the implications of unilateral carbon policy in the electricity market. Electricity differs from other tradable goods in many aspects. First, it is a homogeneous good, meaning that the electricity produced in any region or energy source are perfect substitutes. Second, electricity trade flow is physically constrained by the transmission capacity. Therefore, the risk of firms reallocating depends both on the carbon pricing and the available trade capacity. Third, renewable intermittency signifies the weather-dependency of electricity generation from a renewable source. Therefore, trade policies may have state-dependent effects. This paper contributes to the literature by providing new insights into the choices of unilateral carbon policies for electricity trading.

A few studies focus on carbon leakage in the electricity sector. Fowlie (2009) investigates the extent to which market structure could affect the effectiveness of incomplete market-based environmental regulation. She finds that depending on the competitiveness of the industry and the characteristics of firms under regulation, incomplete regulation may out-perform complete regulation in terms of industry emission and welfare. Chen (2009) estimates the short-run effect of regional cap-and-trade policies on carbon leakage and emission spillover in a transmission-constrained network. Sauma (2012) analyzes the conditions under which carbon leakage would occur under a cap-and-trade program. These existing studies omit the consideration of renewable intermittency on carbon leakage and do not discuss the potential policy instruments that can be used to mitigate leakage.

The remainder of this paper is organized as follows. In Section 2, we lay out our model and characterize the market equilibrium conditions. In Section 3, we analyze the optimal energy mix with Pigouvian emissions taxes in both countries, which serves as the benchmark for optimal capacity investment, consumption level, and emissions. In Section 4, we consider different unilateral climate policy designs and analyze the conditions such that the optimal energy mix can be achieved. We analyze the optimal tax level of 1) only a unilateral emissions tax, 2) emissions tax plus a border tax, and 3) recycling tax renewable with a renewable subsidy. In Section 5, we summarize the optimal policies and discuss the implications of different policy designs on carbon leakage.

2 A model of electricity trade with intermittent renewables and climate policy

Consider two countries A and B denoted by j.[3]

Electricity generation

In each country, electricity can be generated from two technologies: a fully controllable polluting thermal power f (e.g., coal, gas) and an intermittent clean renewable energy source i (e.g., wind, solar).

For the thermal power, the installed capacity K_{jf} ($j \in \{A, B\}$) has a constant unit capacity cost r_f. The fuel and operational cost of producing q_{jf} kilowatt-hour (kWh) of electricity is c_j, if it does not exceed the installed capacity, i.e., $q_{jf} \leq K_{jf}$.

For the intermittent renewables, we follow the notation of Ambec and Crampes (2019). The competitive renewable producers differentiate in their per unit cost of renewable capacity installment r_i. It varies depending on technology and location (weather conditions, proximity to consumers, etc.) in the range $[\underline{r}_i, +\infty)$ according to the density function f and the cumulative function F. For each producer, the maximum capacity they can install is $\bar{K}$.

The production of renewables depends on the prevailing weather conditions. There are two states of nature $s \in \{l, h\}$ with high (h) and low (l) renewables output. In the high state, renewables can generate output at full capacity K_i, and the marginal production cost is normalized to zero. In the low state, the renewables are inactive, with zero output. The two states occur with the exogenous probabilities ν and $1 - \nu$ respectively, which capture the degree of intermittency of the renewables.

Environmental damage

The electricity produced by thermal power is polluting. It emits local pollutant like SO_2,

[3]The model framework can be applied to any regions that can make independent environmental or trade policies. For example, the federal states in the U.S..

NO_x, PM2.5, or more global ones like CO_2. Country A cares about the environmental damage caused by pollution while country B does not care. Country A assigns a constant marginal damage δ for each kilowatt-hour of thermal powered of electricity produced on its territory. It weights the marginal damage of thermal power produced within country B by ϕ so that the marginal damage of one kilowatt-hour from B's thermal power plans is $\phi\delta$ with $0 \leq \phi \leq 1$. The parameter ϕ captures pollution dispersion across space: the pollutant is purely local for $\phi = 0$ (e.g., particulates within a big territory) and global $\phi = 1$ (e.g., greenhouse gas). For both local and global pollutant, i.e., pollutants that partly cross borders like SO_2 or NO_x, we have $0 < \phi < 1$. Throughout the paper, we focus the analysis on policies correcting for carbon emissions ($\phi = 1$). However, the analysis can be easily applied to other pollutants by taking ϕ at different values.

Competitive wholesale and retail markets

In the wholesale market, price is state-dependent denoted by p_j^s. Without loss of generality, we denote the carbon tax in country j imposed on per kilowatt-hour of electricity generation by τ_j, with $\tau_j = 0$ corresponding to no tax. We assume perfect competition in the electricity sector: firms are price-takers and entry in the industry is free. Firms invest in production capacity for each technology and choose production level in each states of nature given prices and the carbon tax.

The thermal producers' profit is:

$$\Pi_{jf} = \nu(p_j^h - (c_j + \tau_j))q_{jf}^h + (1-\nu)(p_j^l - (c_j + \tau_j))q_{jf}^l - r_f K_{jf}. \tag{1}$$

The renewable producers' profit is:

$$\Pi_{ji} = \nu p_j^h \bar{K} - r_i \bar{K}. \tag{2}$$

The demand from final consumers is $Q_j = D(p_j)$, where p_j stands for the retail price in country j. The retail price is constant across states of natures. Consumers in each country derive gross utility $S(Q_j)$ from the consumption of Q_j kWh of electricity. $S(\cdot)$ is continuous and twice differentiable with $S' > 0$ and $S'' < 0$. $S'(0)$ is assumed to be large so that it is always efficient to have some electricity consumption. Moreover, rationing is not allowed, i.e., there can be no partial blackouts. Retailers buy electricity in wholesale price and sell it in the retail market. Their expected profit is:

$$\Pi_{jc} = p_j - \nu p_j^h + (1-\nu)p_j^l \tag{3}$$

The zero-profit condition under free-entry leads to $\Pi_{jf} = 0$ for all thermal producers, $\Pi_{ji} = 0$ for the marginal renewable producers and $\Pi_{jc} = 0$ for retailers. Denote the marginal cost renewable capacity of the marginal producers as $\tilde{r}_i \geq \underline{r}_i$. The active wind power producers, i.e., those with $\underline{r}_i \leq r_i < \tilde{r}_i$, obtain inframarginal profits. The total installed renewable capacity $K_i = \bar{K}F(\tilde{r}_i)$. We assume that across the two markets, producers can trade with no transaction cost up to the transmission capacity K_t.

Transmission market

Electricity can be imported or exported up to the capacity limit K_t of the transmission lines. However, at any given time, the net electric current flows in one direction, and the net flow quantity is denoted by x^s ($s \in \{h, l\}$). Transmission line losses are assumed to be zero.

The market equilibrium conditions are such that the consumption in each country is met with their own production net of import/export. Moreover, with the assumption of no line loss in transmission, the quantity exported must equal to the quantity imported in both states of nature.

Environmental policy

The government in country A cares about environmental damage and chooses that optimal environmental tax that maximizes social welfare in country A defined by:

$$W_A = S(Q_A) + \Pi_{Af} + \Pi_{Ai} - (\delta E_A + \phi\delta E_B) + R_A, \tag{4}$$

where $S(Q_A) = \int_{p_A}^{\bar{p}_A} D(p)dp$ denotes the consumers' surplus, $E_j = \nu q_{jf}^h + (1-\nu)q_{jf}^l$ are emissions in country j for $j = A, B$, and $R_A = \tau_A\big(\nu_A q_{Af}^h + (1-\nu_A)q_{Af}^l\big)$ is the emissions tax revenue.

3 Optimal energy mix with interconnection

Throughout the paper, we make the assumption that country B has a lower marginal cost of thermal energy ($c_B < c_A$). Therefore, opening to trade for country A has economic gains of increased efficiency and reduced cost. However, trading with a country that does not care about the environment may dampen its control over emissions. It might increase environmental damage and, therefore, reduce welfare.

In this section, we investigate what would be the energy mix that the government in country A would like to implement if it could tax emissions in *both* countries. It would tax emissions at rate δ in country A and $\phi\delta$ in country B per kilowatt-hour. We refer to this energy mix as the optimal energy mix with interconnection. We assume that the power line transmission capacity K_t is given (exogenous to both countries), and that it limits electricity trade at least in one state of nature (mostly in state l for thermal power). The case K_t not binding is detailed in Appendix A.2. Under our assumption of perfect competition and zero profit for thermal power, the optimal energy mix with interconnection the energy mix maximizes the countries' joint welfare with environmental damage reflecting country A's tastes.

Before describing the optimal energy mix with interconnection, we make three observations. First, since thermal power equipment is costly, it is used at full capacity in state l, i.e. $q^l_{jf} = K_{jf}$ for $j = A, B$. Second, since the renewable energy source has no operating cost, all the energy produced by renewables (if any) will be supplied to consumers, i.e. $q^h_{ji} = K_{ji}$ and $q^l_{ji} = 0$ for $j = A, B$. Third, since the retailing pice of electricity is fixed, consumption is the same in both states of nature determined by $Q_j = D(p_j)$ for $j = A, B$.

Lemma 1. *The optimal energy mix with interconnection is such that:*

(a) no renewables: $\delta < \frac{r_i}{\nu} - c_A$

$p^s_A = p_A = c_A + \delta + r_f$, $p^s_B = p_B = c_B + \phi\delta + r_f$;

$K_{Af} = D(p_A) - K_t = q^s_{Af}$, $K_{Ai} = 0$, $q^s_{Bf} = K_{Bf} = D(p_B) + K_t$.

(b) renewable and thermal energy in state h: $\frac{r_i}{\nu} - c_A \leq \delta < \underline{\delta}_A$

$p^h_A = c_A + \delta$, $p^l_A = c_A + \delta + \frac{r_f}{1-\nu}$, $p_A = \nu p^h_A + (1-\nu)p^l_A = c_A + \delta + r_f$, $p^h_B = c_B + \phi\delta$, $p^l_B = c_B + \phi\delta + \frac{r_f}{1-\nu}$;

$K_{Af} = D(p_A) - K_t$, $K_{Ai} = \bar{K}F(\nu(c_A + \delta))$, $q^h_{Af} = D(p_A) - K_t - K_{Ai}$, $K_{Bf} = q^s_{Bf} = D(p_B) + K_t$;

$\underline{\delta}_A$ *is such that* $K_{Ai} = \bar{K}F(\nu(c_A + \underline{\delta}_A)) = D(c_A + \underline{\delta}_A + r_f) - K_t$.

(c) renewable-energy-only in state h in country A: $\underline{\delta}_A \leq \delta < \underline{\delta}_B$

$p^h_A = \frac{\tilde{r}_{Ai}}{\nu} > c_B + \phi\delta$, $p^l_A = c_A + \delta + \frac{r_f}{1-\nu}$, $p_A = (1-\nu)(c_A + \delta) + r_f + \tilde{r}_{Ai}$, $p^h_B = c_B + \phi\delta$, $p^l_B = c_B + \phi\delta + \frac{r_f}{1-\nu}$, $p_B = \nu p^h_B + (1-\nu)p^l_B = c_B + \phi\delta + r_f$;

$K_{Af} = D(p_A) - K_t$, $K_{Ai} = \bar{K}F(\nu p^h_A)$, $q^h_{Af} = 0$, $q^s_{Bf} = K_{Bf} = D(p_B) + K_t$;

where $\tilde{r}_{Ai}$ *is defined by* $\bar{K}F(\tilde{r}_{Ai}) = D((1-\nu)c_A + \delta + r_f + \tilde{r}_{Ai})$ *and* $\underline{\delta}_B$ *by* $\bar{K}F(\nu(c_B + \phi\underline{\delta}_B)) = D(c_B + \phi\underline{\delta}_B + r_f) - K_t$.

(d) trade of renewable energy below capacity: $\underline{\delta}_B \leq \delta < \bar{\delta}$

$p^h_A = c_B + \phi\delta$, $p^l_A = c_A + \delta + \frac{r_f}{1-\nu}$, $p_A = \nu(c_B + \phi\delta) + (1-\nu)(c_A + \delta) + r_f$, $p^h_B = c_B + \phi\delta$, $p^l_B = c_B + \phi\delta + \frac{r_f}{1-\nu}$, $p_B = \nu p^h_B + (1-\nu)p^l_B = c_B + \phi\delta + r_f$;

$K_{Af} = D(p_A) - K_t$, $K_{Ai} = \bar{K}F(\nu p_A^h)$, $q_{Af}^h = 0$, $K_{Bf} = D(p_B) + K_t$ $q_{Bf}^h = D(p_B) + D(p_A) - K_{Ai}$;

$\bar{\delta}$ is such that $\bar{K}F(\nu(c_B + \phi\bar{\delta})) = D(c_B + \phi\bar{\delta} + \frac{r_f}{1-\nu}) + K_t$.

(e) export of renewable energy up to power line capacity: $\bar{\delta} \leq \delta$

$p_A^h = \frac{\tilde{r}_{Ai}}{\nu}$, $p_A^l = c_A + \delta + \frac{r_f}{1-\nu}$, $p_A = (1-\nu)(c_A + \delta) + r_f + \tilde{r}_{Ai}$, $p_B^h = c_B + \phi\delta$, $p_B^l = c_B + \phi\delta + \frac{r_f}{1-\nu}$, $p_B = c_B + \phi\delta + r_f$;

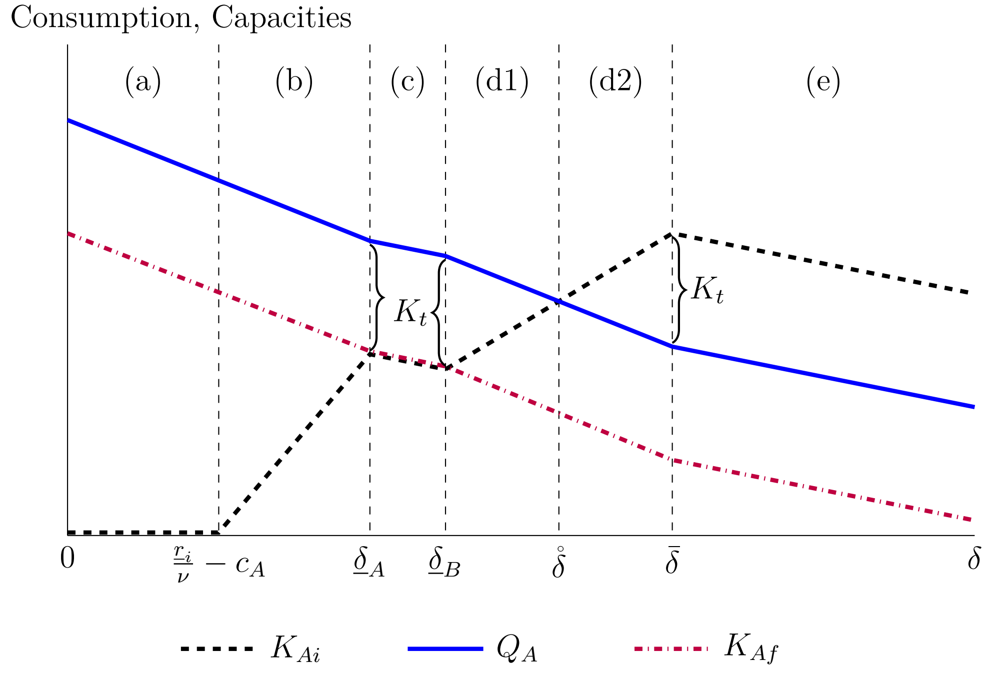
$K_{Af} = D(p_A) - K_t$, $K_{Ai} = \bar{K}F(\tilde{r}_{Ai}) = D(p_A) + K_t$, $q_{Af}^h = 0$, $q_{Bf}^h = D(p_B) - K_t$, $q_{Bf}^l = K_{Bf} = D(p_B) + K_t$;

where $\tilde{r}_{Ai}$ *is such that* $\bar{K}F(\tilde{r}_{Ai}) = D((1-\nu)(c_A + \delta) + r_f + \tilde{r}_{Ai}) + K_t$.

Proof. See Appendix A.1 □

Figure 1 illustrates the optimal consumption level, thermal and renewable capacities in Lemma 1 as a function of the marginal damage/carbon tax.

Figure 1: Optimal investment and consumption in country A under constrained transmission



We now comment on the optimal energy mix described in Proposition 1.

In case (a), the carbon tax is too low to justify any investment in renewable capacity. Both countries use only thermal power to generate electricity. The power line is used in one direction in both states of nature to export K_t kilowatt-hours of cheaper electricity from B to A. The retail price is higher in A than in B because of the binding transmission constraint. The marginal benefit of extending the power line capacity is given by the price difference $p_A - p_B = c_A - c_B + \delta(1-\phi)$.

In case (b), renewable energy in country A is complemented with thermal power in state h. The power line is still used at full capacity to transfer K_t kilowatt-hours of cheap thermal from B to A in both states of nature. The marginal benefit of extending the transmission capacity is the same as in case (a).

In case (c), country A generates with only renewable energy in state h. The power line is used under full capacity to transfer cheap thermal from B to A in both states of nature as in cases (a) and (b). However, the marginal benefit of extending transmission capacity is now equals to $p_A - p_B = (1-\nu)(c_A+\delta) + \tilde{r}_{Ai} - c_B - \phi\delta < c_A - c_B + \delta(1-\phi)$. The last inequality is because the last unit of deployed renewable capacity has a lower cost that the thermal power in country A given the carbon tax ($\frac{\tilde{r}_i}{\nu} < c_A + \delta$). It is therefore lower than in cases (a) and (b).

In case (d), the power line is used below capacity in state h in different directions depending if δ is higher or lower than $\mathring{\delta}$ defined by $\bar{K}F(\nu(c_B + \phi\mathring{\delta})) = D(c_B + \phi\mathring{\delta} + r_f)$, i.e., where the two upper lines cross in Figure 1. In case (d1), $\delta < \mathring{\delta}$, country A imports less than K_t of power in state h. In case (d2), $\delta > \mathring{\delta}$, country A do not import anymore thermal power in state h (only in state l) and exports renewable energy to B. The power line is used in opposite directions depending on the state of nature: from B to A in state l and A to B in state h. Trade occurs at full capacity in state l like in cases (a), (b) and (c). In both cases (d1) and (d2), electricity wholesale prices are equal in both countries state h (power line capacity not binding), while A has a higher price than B in state l. The marginal benefit of increasing transmission capacity is now state-contingent, zero in state h and $p_B^l - p_B^l = c_A - c_B + (1-\phi)\delta$ in state l. It thus equals to $(1-\nu)(p_B^l - p_B^l) = (1-\nu)(c_A - c_B + (1-\phi)\delta)$ on average.

In case (e), country A exports K_t kilowatt-hours of renewable energy to B. The power line is used at full capacity to exchange power in opposite directions depending on the state of nature. Electricity is cheaper in A than B in state h while the reverse holds in state l. The marginal benefit of increasing transmission capacity is $p_B^h - p_A^h = c_B + \phi\delta - \frac{\tilde{r}_{Ai}}{\nu}$ in state h and $p_B^l - p_B^l = c_A - c_B + (1-\phi)\delta$ in state l. On average, the benefit of one more kilowatt of transmission is $\nu(p_B^h - p_A^h) + (1-\nu)(p_B^l - p_B^l) = \nu(c_B + \phi\delta - \frac{\tilde{r}_{Ai}}{\nu}) + (1-\nu)(c_A - c_B + (1-\phi)\delta)$.

4 Climate policy with interconnection

4.1 Unilateral carbon tax

Consider now that country A can only tax emissions in its own jurisdiction and the carbon tax in country B is normalized to zero ($\tau_A > 0$, $\tau_B = 0$). We are interested in knowing whether the government in country A should adjust the imposed carbon tax beyond or below the Pigouvian level. Moreover, we analyze implications of a unilateral carbon tax on global emissions and renewable capacity investment.

We can easily establish that in the absence of a carbon tax in country B, since $c_A > c_B$, the wholesale prices in country A are always higher than that in country B for any carbon tax rate τ_A. Electricity retailers in country A purchase electricity where its is cheaper. They thus import it from country B. If the transmission capacity K_t exceeds the demand of electricity in country A at price equals to B's long term marginal costs $c_B + r_f$, then all electricity consumed in A is imported for B, no electricity is generated in country A. Formally if $D(c_B + r_f) \leq K_t$ then $K_{Af} = K_{Ai} = q^s_{Af} = 0$ for $s = l, h$. Otherwise, the transmission line is used at full capacity in both states of nature, K_t kilowatt-hours is imported from B, the rest being produced locally. the energy mix in country A is then impacted by the carbon tax as described in the following lemma.

Lemma 2. *With a unilateral carbon tax τ_A in country A, the equilibrium prices and quantities are such that:*

i K_t binding: $D(c_B + r_f) > K_t$
$p^s_B = p_B = c_B + r_f$, $K_{Bf} = D(p_B) + K_t$;

(a) no renewables: $\tau_A < \frac{r_i}{\nu} - c_A$
$p^s_A = p_A = c_A + \tau_A + r_f$;
$q^s_{Af} = K_{Af} = D(p_A) - K_t$, $K_{Ai} = 0$.

(b) renewable energy and thermal in state h: $\frac{r_i}{\nu} - c_A \leq \tau_A < \underline{\tau}_A$
$p^h_A = c_A + \tau_A$, $p^l_A = c_A + \tau_A + \frac{r_f}{1-\nu}$, $p_A = \nu p^h_A + (1-\nu)p^l_A = c_A + \tau_A + r_f$;
$q^h_{Af} = K_{Af} - K_{Ai}$, $q^l_{Af} = K_{Af} = D(p_A) - K_t$, $K_{Ai} = \bar{K}F(\nu p^h_A)$;
$\underline{\tau}_A$ *is such that* $K_{Ai} = \bar{K}F(\nu(c_A + \underline{\tau})) = D(p_A) - K_t$.

(c) renewable-energy-only in state h in country A: $\underline{\tau}_A \leq \tau_A$
$p^h_A = \frac{\tilde{r}_{Ai}}{\nu}$, $p^l_A = c_A + \tau_A + \frac{r_f}{1-\nu}$, $p_A = (1-\nu)(c_A + \tau_A) + r_f + \tilde{r}_{Ai}$;
$q^h_{Af} = 0$, $q^l_{Af} = K_{Af} = K_{Ai} = D(p_A) - K_t$.

ii K_t *not binding:* $D(c_B + r_f) \leq K_t \; \forall \; \tau_A \geq 0$, $p^s_A = p_A = p_B = c_B + r_f$; $q^s_{Af} = K_{Af} = K_{Ai} = 0$, $K_{Bf} = D(p_A) + D(p_B)$.

To determine the optimal level of τ_A, the government maximizes the social welfare of country A taking the equilibrium level of prices in Lemma 2 as given.

$$\max_{\tau_A} \quad W_A \tag{5}$$

where

$$W_A = \underbrace{S(Q_A)}_{\text{WTP}} \underbrace{- c_A(\nu q^h_{Af} + (1-\nu)K_{Af}) - p_B K_t - r_f K_{Af} - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i)}_{\text{Total cost}} - \underbrace{\delta\big(\nu q^h_{Af} + (1-\nu)K_{Af} + \phi(Q_B + K_t)\big)}_{\text{Environmental damage}}$$

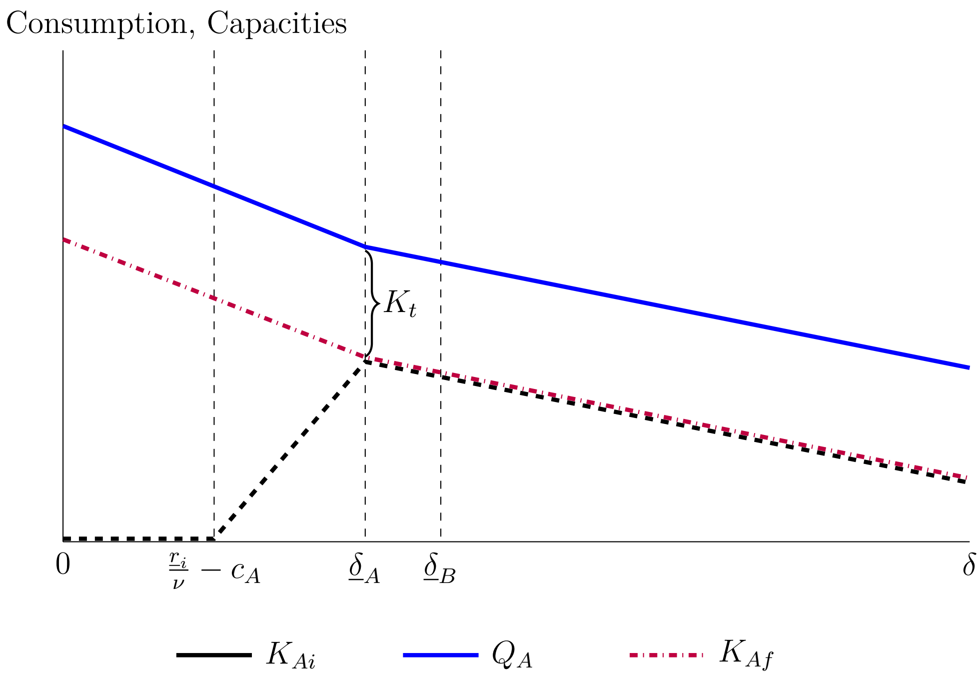
Proposition 1. *The optimal carbon tax in country A is equal to the marginal damage of emissions* $\tau_A = \delta$*. It is effective only if the transmission constraint is binding, that is if* $K_t < D(c_B + r_f)$*.*

Proof. See Appendix A.3. □

The intuition for Proposition 1 is straightforward. When the transmission constraint is binding, country A imports from B up to the line capacity. The carbon tax only affects local production cost and in turn the local consumption level. Therefore, country A cannot be better off by adjusting the carbon tax away from the Pigouvian level. However, when there is unlimited line capacity, whatever level of carbon tax country A levies on local production is not effective, as all electricity consumption comes from thermal production in B. Thus, the carbon price does not reduce carbon emissions.

Figure 2 illustrates the equilibrium consumption level, thermal and renewable capacities as a function of the optimal unilateral carbon tax (referred to as “uni-tax”).

Figure 2: Equilibrium investment and consumption in country A with unilateral carbon tax under constrained transmission



Compare Lemma 1 and 2, illustrated by Figure 1 and 2 respectively, we can make several observations regarding the equilibrium prices and quantities in country A. First, a carbon tax implements the optimal energy mix with interconnection described in cases (a) to (c) in Lemma 1 - that is when $\delta < \underline{\delta}_B$ - but only in country A and when the transmission capacity is binding. It indeed leads to the same prices, electricity trade, investments in generation and production in country A. Yet since emissions are not taxed in country B, too much pollution is emitted outside A when harmful, that is when $\phi > 0$.

Second, if $\delta > \underline{\delta}_B$, the uni-tax leads to over investment in thermal capacity and under investment in renewable capacity. The gap between the quantities increases with transmission capacity. A bi-lateral carbon tax can correct for the emission externality in country B and avoid too much thermal power to be imported at high δ, whereas the uni-tax cannot correct for such externality and result in higher consumption level and lower renewable capacity in country A.

Third, the carbon tax does not impose additional leakage risk. We define carbon leakage as the emission that would have occurred within the jurisdiction in the absence of trade. For country A, leakage happens for any $K_t > 0$ under the assumption $c_A > c_B$. The level of leakage would thus depend on the level of K_t. Imposing a uni-tax does not increase the carbon emission outside the jurisdiction. The leakage can be reduced by limiting K_t.

The analysis shows that since the uni-tax cannot effectively change the thermal production cost in B, it cannot correct for the emissions externality as long as $\phi > 0$. It also leads to under-investment of renewable capacity when it is optimal to do so, that is for $\delta > \underline{\delta}_B$. Subsequently, we investigate whether a border adjustment tax can implement the optimal energy mix with interconnection when $\delta > \underline{\delta}_B$.

4.2 Border Adjustment Tax

Assume now country A imposes a border adjustment tax on each unit of thermal electricity imported from country B.[4] Let use denote the border adjustment tax (BAT) by τ_x. Intuitively, a BAT increases the price of imported electricity, which can reduce thermal import and increase local renewable production. We are interested in understanding the optimal level of the BAT, when it is effective, and whether it can replicate the optimal prices at least in country A.

We assume for now that country B cannot build renewable power. It can simply be because they do not have access to the technology, building renewables are prohibitively expansive, or due to other political constraints. We relax this constraint in further analysis.

Three observations regarding τ_x can be established. First, regardless of the level of τ_x, B never imports from A because the BAT does not affect the wholesale prices in country B. Thus, the BAT has no effect over the consumption level in B. Second, in state l, country A imports from B if and only if $p^l_A > p^l_B + \tau_x$, which, by replacing prices by marginal costs including taxes, leads to $\tau_x < c_A - c_B + \tau_A$. Depending on the transmission capacity, A imports up to the transmission constraint or to domestic demand. Third, in state h, depending on the relative after tax price in A and B, country A would not import anything, import below line capacity, or import at line capacity from country B.

Figure 3 illustrates the above situations. The market equilibrium responding to different levels of border tax can further be categorized to four ranges:

i No additional effect if transmission limited: $\tau_x < \underline{\tau}_x$

A low level of BAT has no effect on the trade flow compare to just a uni-tax. As the uni-tax and the optimal production and consumption level are equivalent in country A if $\delta < \underline{\delta}_B$, there will be no need for a BAT in this range of δ.

However, if there is no line capacity limit, the BAT is effective in reducing excessive consumption in country A.

[4] The tax imposed on the carbon content of imported good is referred to as a border carbon adjustment tax. For electricity trade, the border tax can also be levied on other pollutants from thermal power.

ii Reduced import in state h: $\underline{\tau}_x \leq \tau_x < \bar{\tau}_x$

A BAT in this range makes the transmission contraint binding (or import up to consumption) only in state l ($0 < x^h_A < K_t, x^l_A = K_t$). In state h, the BAT is effective in decreasing thermal import, which in turn increases renewable capacity investment.

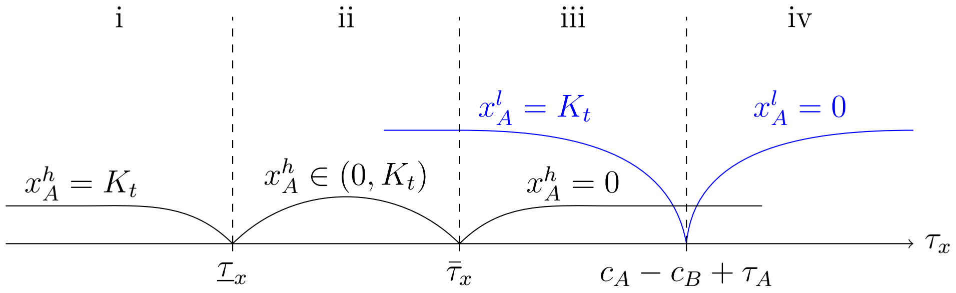
iii No import in state h: $\bar{\tau}_x \leq \tau_x < c_A - c_B + \tau_A$

A BAT in this range means there is import only in state l up to the transmission constraint ($x^h_A = 0, x^l_A = K_t$). In state h, A uses only renewable capacity to satisfy demand.

iv No import in both states: $\tau_x \geq c_A - c_B + \tau_A$

A BAT in this range limits trade in both states. This is equivalent as reducing transmission capacity to zero.

Figure 3: Illustration of the trade flow with different levels of border adjustment tax (binding transmission)



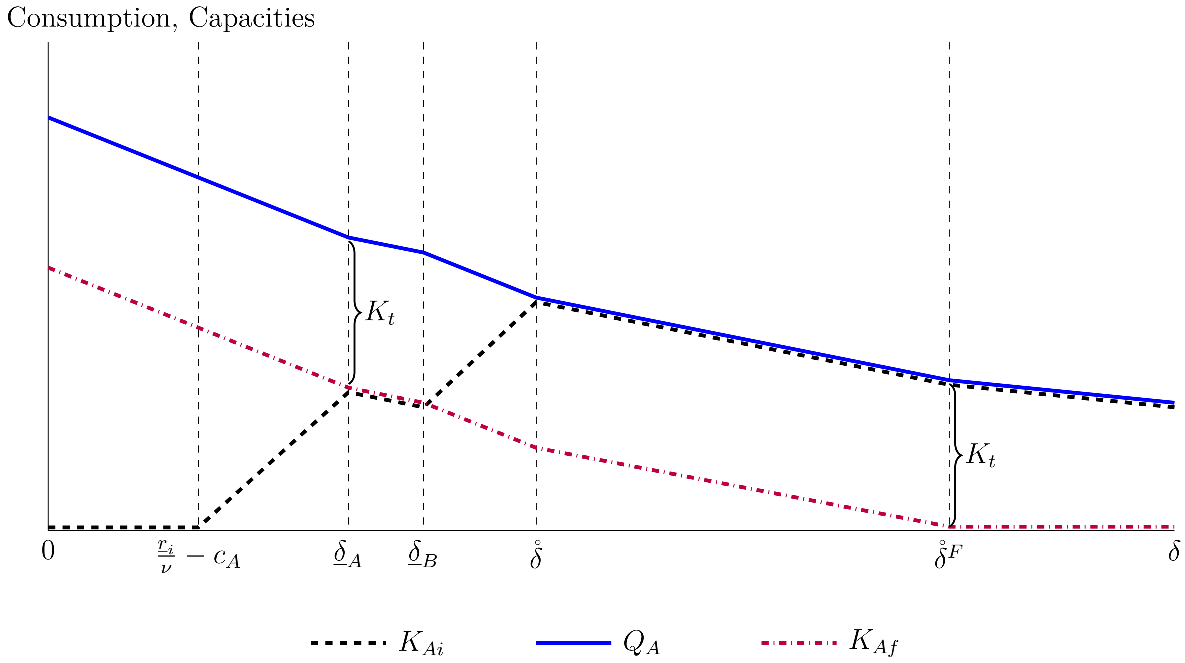
Note: If the line capacity is not binding, all K_t are replaced with Q_A. $\underline{\tau}_x = \frac{\underline{r}_{Ai}}{\nu} - c_B$ and $\bar{\tau}_x = \frac{\bar{r}_{Ai}}{\nu} - c_B$.

Proposition 2. *The optimal border adjustment tax in country A is equal to the weighted marginal damage of emissions $\tau_x = \phi\delta$. It is effective only when the transmission constraint is not binding in at least one state, that is if $K_t > D(p_A) - \bar{K}F(\nu(c_B + \phi\delta))$ and $\delta > \underline{\delta}_B$, or if $K_t > D(c_B + r_f)$. The optimal level of carbon tax does not change when combined with a border adjustment tax.*

Proof. See Appendix A.4. □

Figure 4 illustrates Proposition 2 and shows the consumption, production and capacities in country A with optimal carbon tax and border tax.

Figure 4: Equilibrium capacity and consumption in country A under optimal border tax and carbon tax



The intuition for Proposition 2 can be understood by comparing the equilibrium prices with the carbon tax and a BAT with the prices of the optimal energy mix with trade described in Lemma 1. With $\tau_A = \delta$ and $\tau_x = \phi\delta$, we obtain the optimal prices when thermal power is imported in country A, i.e. $p_B + \tau_x = c_B + r_f + \phi_A \delta$ or $p_B^h + \tau_x = c_B + \frac{r_f}{1-\nu} + \phi\delta$. If $\delta < \underline{\delta}_B$, the transmission capacity constraint is biding in both states of nature with those prices, i.e. see cases (a) to (c) of Lemma 1. Transmission capacity limits imports of thermal power in country A anytime so that the BAT is not needed. If $\underline{\delta} < \delta < \mathring{\delta}$, thermal power is still imported in country A but below transmission capacity in state h to complement renewable production from A. The BAT is needed to avoid further import of thermal power in state h. In state l, the border tax is useless except for increasing government revenue. For $\delta > \mathring{\delta}$, the lack of carbon tax in country B makes renewable not competitive in B so they cannot be exported from country A without a subsidy. Hence the carbon tax and BAT alone cannot implement the optimal energy mix in country A because of underinvestment in renewables.

Importantly, when the transmission capacity is not binding, for example when $\delta > \mathring{\delta}^F$ in Figure 4, where $\mathring{\delta}^F$ is defined by $\bar{K}F(\nu(c_B + \phi\mathring{\delta}^F)) = D(c_B + r_f + \phi\mathring{\delta}^F)$, the border tax is always effective for reducing import in both states. Here, the BAT is a substitute to limited transmission capacity.

It is apparent from the analysis that the BAT is not effective in leveling the playing field in country B. There is under investment of renewable capacity compared to the optimal level in the absence of other policy instruments. The widely discussed policy instruments to deal with this issue are output based rebate (OBR) schemes and emission allowances (Böhringer, Fischer, et al. 2014; Böhringer, Rosendahl, et al. 2017; Martin et al. 2014). These policies refund the levied domestic carbon tax to the producers if their output is used for export. Directly applying OBR in electricity trade cannot foster renewable export since the energy itself is clean. By analogy, we consider a subsidy for renewable capacity investment. It can be regarded as allocating "green permits" to renewable producers that can be sold to thermal producers at a fixed rate. In the next part, we investigate the effect of renewable subsidies.

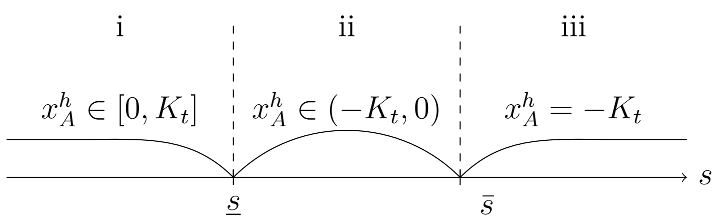
4.3 Renewable Subsidy

In this section, we consider the possibility of recycling the tax revenue as a subsidy for domestic or international renewable capacity. The firms of country A can choose to invest locally or internationally, using their own technology. The subsidy takes the form of a per unit subsidy on renewable capacity with a flat rate s. The total subsidy given is $S = sK_i$, which comes from the total tax revenue collected.

4.3.1 Domestic Renewable Subsidy

First consider subsidizing domestic investment. The subsidy reduces the feed-in cost of renewable production, and in turn, can potentially decrease the equilibrium wholesale price in state h ($p_A^h = \min\{c_A + \tau_A, \frac{\tilde{r}_{Ai}-s}{\nu}\}$). Note that for $\delta < \mathring{\delta}$, the carbon tax with border tax can restore the optimal prices in country A. There is no need for the subsidy. Therefore, we focus on the analysis for $\delta \geq \mathring{\delta}$.

Figure 5: Illustration of the trade flow with different levels of subsidy rate (binding transmission)



Note: If the transmission constraint is not binding, K_t is replaced with Q_A in scenario i, and with Q_B in scenario ii and iii. $\underline{s} = \tilde{r}_{Ai}(Q_A) - \nu c_B$ and $\bar{s} = \tilde{r}_{Ai}(Q_A + K_t) - \nu c_B$.

Similar to the BAT, depending on the level of s, there are the following scenarios for a binding transmission constraint as illustrated in Figure 5.

i No additional effect compare to optimal carbon tax with border tax: $s < \underline{s}$
With a subsidy in this range, the renewable capacity is not enough to cover demand in state h. A uni-tax with a BAT can achieve the same result. Therefore, a subsidy is not needed for $\delta < \mathring{\delta}$.

ii Renewable export below line capacity in state h: $\underline{s} \leq s < \bar{s}$
With a subsidy in this range, the country A has excess renewable capacity for export in state h. For country B to be willing to import, the after-subsidy unit price need to be weakly lower than c_B.

iii Renewable export at full line capacity in state h: $s \geq \bar{s}$
For a subsidy rate in this range, prices are $p_A^h = \frac{\tilde{r}_{Ai} - s}{\nu}$ and $p_A = (1-\nu)(c_A + \tau_A) + \tilde{r}_{Ai} - s + r_f$. Note that since capacity is costly, it is inefficient to have renewable capacity greater than $D(p_A) + K_t$. Thus, there is no need for $s > \bar{s}$. $\bar{s}$ is such that $\bar{K}F(\nu c_B + \bar{s}) = D(p_A) + K_t$.

Proposition 3. *The subsidy on renewable capacity $s = \nu\phi\delta$ implements the optimal energy mix with interconnection in country A when combined with an emission tax τ_A and a border tax $\tau_x = \phi\delta$ when $\mathring{\delta} < \delta < \bar{\delta}$. The emission tax should be set at a rate $\tau_A = \delta(1 + \frac{\nu\phi\delta}{1-\nu})$ higher than the marginal damage δ to avoid excess consumption.*

Proof. See Appendix A.5. □

Figure 6: Equilibrium capacity and consumption in country A under renewable subsidy

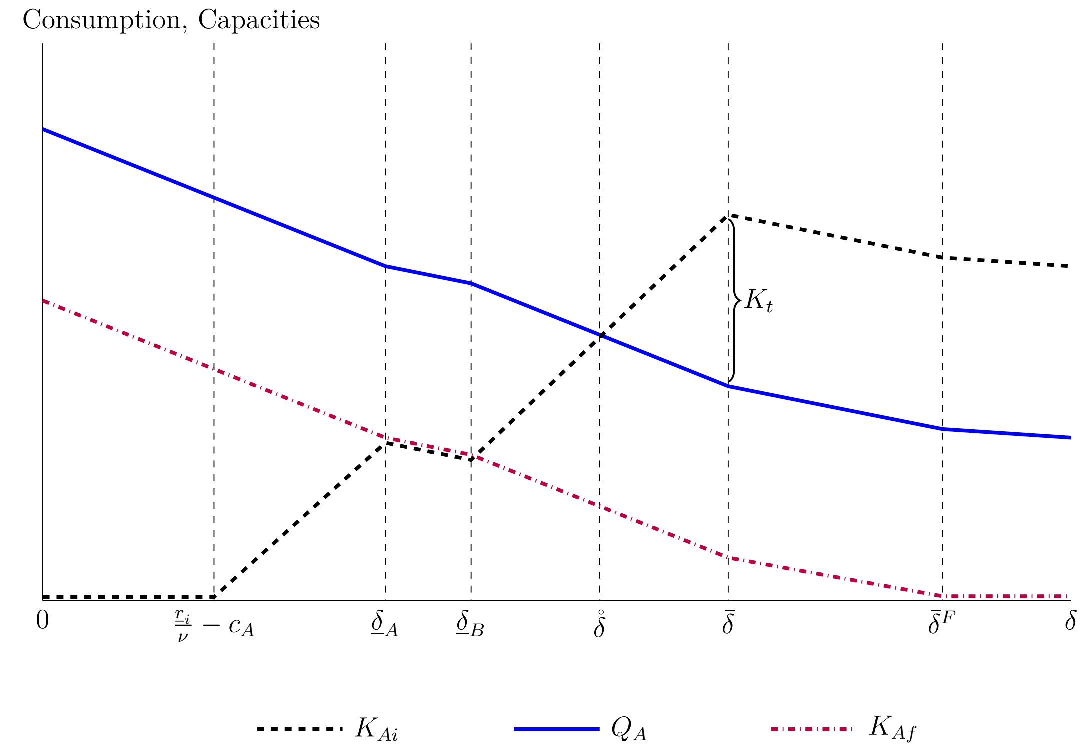


Figure 6 illustrates Proposition 3 and shows the consumption, production and capacities in country A with optimal carbon tax, border tax, and renewable subsidy.

If $\delta > \mathring{\delta}$ (case (d2) and (e) in section 3), having a renewable subsidy can help country A to expand renewable capacity and export to country B in state h. For $\mathring{\delta} < \delta < \bar{\bar{\delta}}$, it could be a subsidy on the power exported at rate $s = \phi\delta$ which reduces electricity price to $p_A^h - \phi\delta = p_B^h$ or a subsidy on capacity at the rate $s = \nu\phi\delta$. For $\delta > \bar{\bar{\delta}}$, the subsidy rate is capped at $\bar{s}$ such that $\bar{K}F(\nu c_B + \bar{s}) = D(p_A) + K_t$. Moreover, the BAT is no longer affective to avoid the crowding out of renewables as the subsidy already ensures renewables to be competitive in country B.[5] Nevertheless, if the government budget is not balanced, the BAT can be used to raise more tax revenue.

Importantly, a higher carbon tax rate needs to go along with a domestic renewable subsidy. The intuitions is simply to compensate for the lowered retail because of the subsidy. Therefore, the carbon tax rate should increase by the $\frac{\nu}{1-\nu}\phi\delta$ (compared to without subsidy), which fully offsets the effect of the subsidy on retail prices.[6]

The analysis suggests that by recycling the carbon tax revenue through a renewable subsidy, we can ramp up renewable capacity and reduce emissions. However, in all cases, there is too much thermal power generation in country B because it is not taxed. The above climate policies can only implement the right investment and consumption outcome in A as well as optimal trading between countries.

4.3.2 International Renewable Subsidy

Alternatively, the renewable subsidy can also be given to producers to invest in renewable capacity in country B. A few additional assumptions need to be made to isolate the difference between domestic and international subsidy. First, we assume that the marginal cost for an additional unit of capacity in country A and B is the same ($\tilde{r}_{Ai}(Q_A) = \underline{r}_{Bi}$).[7] Secondly, the profit of the renewable investment in country B is shared between the two countries determined by a parameter $\theta \in [0, 1]$, with $\theta = 0$ meaning all surplus is captured by country B.[8] Third, we assume that the renewable state in B occurs simultaneously

[5] A special case is when $\delta \geq \bar{\delta}^F$. In this case, country A no longer need local thermal capacity. Thus, the BAT needs to be implement to maintain the competitiveness of renewables.

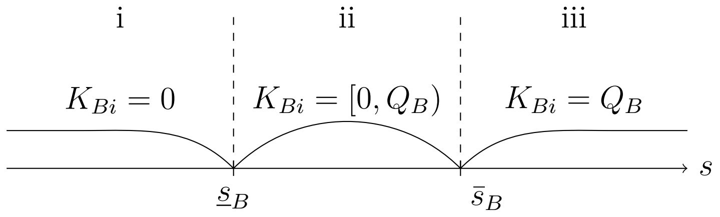
[6] Alternatively, we can implement a consumption tax combined with the renewable subsidy to obtain the optimal prices, similar to the analysis in Böhringer, Rosendahl, et al. (2017). The optimal consumption tax rate equals $\delta((1-\nu) + \nu\phi)$.

[7] Under this assumption, border tax alone cannot induce any investment in B even if they have free access to the same technology.

[8] θ can be interpreted as the share of gains from foreign direct investment in renewable energy. The in-flow country gains from increased local employment, technology spillover, taxation, etc. The out-flow country gains from investment returns, global market share, etc.

with A, so that the two technologies are equivalent regardless of their location. The location of renewables only impact market conditions at the country level.[9]

Figure 7: Illustration of the renewable capacity in country B under different subsidy rates



Note: $\underline{s}_B = \underline{r}_{Bi} - \nu c_B$ and $K(F(\nu c_B + \bar{s}_B) - F(\tilde{r}_{Ai})) = D(c_B + r_f)$.

Depending on the subsidy rate, there are three cases as illustrated in Figure 7.

i No renewables in B: $s < \underline{s}_B$

A subsidy in this range cannot induce any renewable capacity investment in country B. The average marginal cost of renewable power is too high compared to the marginal cost of thermal power ($\underline{r}_{Bi} - s > \nu c_B$).

ii Renewable capacity lower than full demand in B: $\underline{s}_B \leq s < \bar{s}_B$

The renewable capacity in B is up to $K_{Bi} = \bar{K}F(\nu c_B + s) - Q_A$, which gives $p_B^h = c_B$ and $p_B^l = c_B + \frac{r_f}{1-\nu}$

iii Renewable capacity equal to full demand in B: $s \geq \bar{s}_B$

Since capacity is costly, the renewable capacity would not exceed full consumption in B.

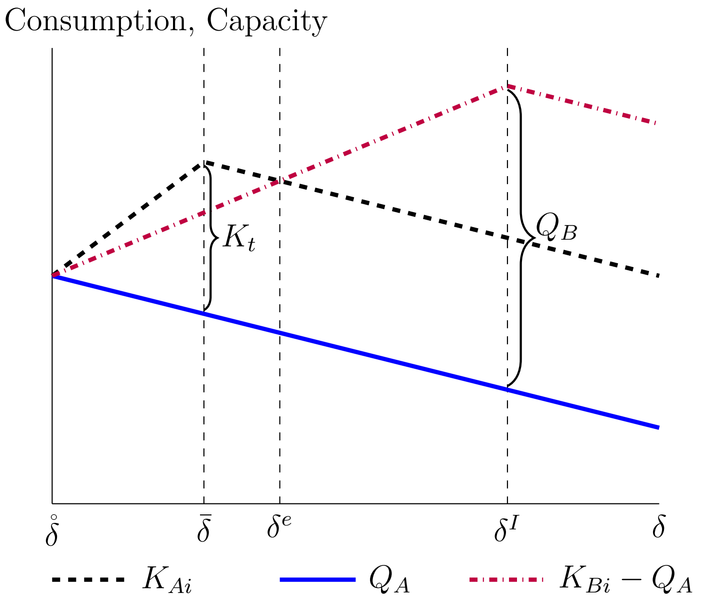
Proposition 4. *Country A subsidizes renewables in country B at rate* $s = \nu((\theta - 1)c_B + \phi\delta)$ *when the power line is used at maximal capacity in state* h.

Proof. See Appendix A.6. □

Figure 8 illustrates Proposition 4 and compares the total renewable capacity under optimal domestic (black line) and international (purple line) subsidy. It is straightforward that the international subsidy rate does not affect the prices in country A. So the optimal level of τ_A and τ_x are consistent with that in section 4.2, where $\tau_A = \delta$ and $\tau_x = \phi\delta$. Unlike in the domestic case, with international subsidy, the BAT is still needed so that renewable capacity in country A remains competitive.

[9] In particular, spreading renewable equipments in different countries is not a strategy to cope with intermittency like in Yang (2020).

Figure 8: Equilibrium renewable capacity and consumption under international renewable subsidy



Note: δ^e satisfies $\bar{K}(F(\theta\nu c_B + \phi\delta^e)\nu) - F(\tilde{r}_{Ai})) = K_t$ and δ^I satisfies $\bar{K}(F(\theta\nu c_B + \phi\delta^I)\nu) - F(\tilde{r}_{Ai})) = D(c_B + r_f)$.

The optimal subsidy rate is $s = \nu((\theta - 1)c_B + \phi\delta)$. If $\theta = 1$, then the subsidy rate is equivalent to the domestic subsidy case, whereas if $\theta < 1$, the subsidy rate is lower than the domestic rate. This only holds for $K_{Bi} < K_t$ ($\delta < \delta^e$ in Figure 8), since the subsidy to induce renewable investment in B is not bounded by K_t. For $\delta > \delta^e$, $K_{Bi} > K_t$. The subsidy is equivalent to relaxing the transmission constraint.

Moreover, if $\theta = 0$, i.e. free licensing of renewable technology, it is still in country A's interested to subsidize $\nu(\phi\delta - c_B)$. Because the value of free licensing (denoted by V_L) is strictly positive.

$$V_L = \underbrace{\nu\phi\delta K_{Bi}}_{\text{avoided emissions}} - \underbrace{\nu(\phi\delta - c_B)K_{Bi}}_{\text{total subsidy}} = c_B K_{Bi} > 0 \tag{6}$$

Subsequently, an interesting question to ask is whether it is more probable to invest in transmission capacity rather than subsidizing internation capacity when $\delta > \delta^e$. To answer this question, we need to compare the additional cost of investing in transmission capacity plus subsidizing domestic capacity to the cost of international subsidy.

Suppose there are two options for the government in country A when $\delta^e < \delta < \delta^I$: 1) invest in transmission capacity and subsidize domestic renewable capacity for export or 2) directly subsidize international renewable capacity. The additional investment in transmission capacity ΔK_t is such that $K_t + \Delta K_t = K_{Bi}$, where K_t is the existing line capacity and K_{Bi} is the renewable capacity in B under international subsidy. Assume a constant marginal cost for the transmission line r_t. For option 1, the total welfare gain in country A is

$$g_1 = \nu c_B \Delta K_t - \bar{K} \int_{r_i^e}^{\tilde{r}_{Bi}} r_i dF(r_i) - (\bar{s}^D + r_t)\Delta K_t \tag{7}$$

For option 2

$$g_2 = \theta(\nu c_B \Delta K_t - \bar{K} \int_{r_i^e}^{\tilde{r}_{Bi}} r_i dF(r_i)) - s^I \Delta K_t \tag{8}$$

We can infer from $\delta = \delta^e$ where country A is indifferent from investing in A or B, that if $r_t = 0$, $g_1 = g_2$. Thus, it is obvious that $\forall r_f > 0$, $g_1 < g_2$, i.e., country A is better off by directly subsidizing investment in B for any cost of transmission lines.

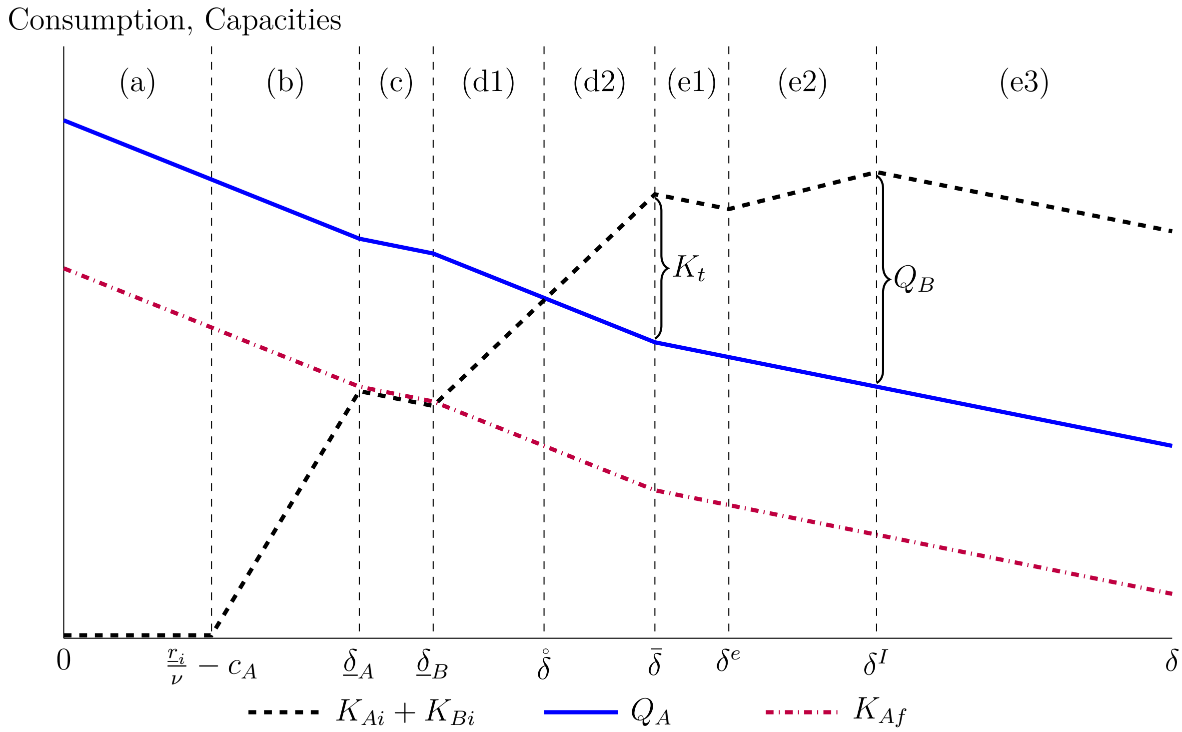
5 Discussion and Policy Implications

Coordination of climate policies at the international level remains a global challenge. Particularly with the trend of growing integration of energy systems across countries, the lack of coordinated policy may exacerbate global emissions. We examine the unilateral policy instruments that may restore the optimal energy mix, at least in the local market. In this section, we summarize some of the key results and discuss the implications on carbon leakage concerns.

5.1 Unilateral climate policy

Figure 9 summarizes the second-best unilateral climate policies for country A when the transmission constraint is binding at least in state l.

Figure 9: Optimal climate policy given increasing marginal emissions damage



In case (a) to (c), only a carbon tax is needed at the Pigouvian level $\tau_A = \delta$ to implement the optimal energy mix in country A. The carbon tax induces sufficient level of renewable capacity in country A. The imports of thermal power do not needed to be taxed because they are limited by the transmission lines which are used under full capacity.

In case (d1), the carbon tax $\tau_A = \delta$ must be complemented by a BAT $\tau_x = \phi\delta$. In this case, the power line capacity should not be used at full capacity when renewables are producing. Hence, the capacity constraint is not binding in the optimal energy mix with interconnection. The power line alone does not prevent importing more than what is optimal. A BAT is required to limit the importations of thermal power from country B. It assigns a value to imported thermal power equals to the marginal damage imposed on country A. It is only effective when renewables are producing.

In case (d2), a carbon tax $\tau_A = \delta(1 + \frac{\phi\nu}{1-\nu})$ plus a domestic renewable subsidy $s^D = \nu\phi\delta$ implement the optimal energy mix. The optimal energy mix with interconnection requires to export green energy to country B. However, since thermal power production is not taxes, green energy produced in country A is not competitive in country B. A domestic subsidy is needed to make it competitive as it reduces the price of electricity in state h, i.e., when the renewables are producing. However, a lower price increases consumption in the retail market which, because consumers are charged constant prices, leads to thermal power over consumption. The carbon tax must be adjusted to compensate the price reduction. Carbon emissions are taxed at a rate higher than the Pigouvian level: $\tau_A = \delta(1 + \frac{\phi\nu}{1-\nu}) > \delta$.

In case (e1), a carbon tax $\tau_A = \delta(1 + \frac{\bar{s}}{1-\nu})$ plus a domestic renewable subsidy $s^D = \bar{s}$ replicates the optimal energy mix. The intuition is the same as case (d2). The only difference is the subsidy rate, where $\bar{s} < \nu\phi\delta$, because it is inefficient to built renewable capacity exceeding the transmission capacity.

In case (e2), a carbon tax $\tau_A = \delta$ combined with a BAT $\tau_x = \phi\delta$, and an international subsidy $s^I = \nu((\theta - 1)c_B + \phi\delta)$ is optimal for country A. A direct international renewable subsidy relaxes the constraint imposed by the transmission capacity, and allows more renewable capacity to be build that can be consumed directly in B. Note that in case (a) to (e1), the climate policies can only implement the optimal energy mix in A and leaves the emissions in B unchecked. With international renewable subsidy, we move towards reducing the emissions in country B. Although there is too much thermal capacity compared to the optimal level, the emissions might be lower than the optimal level if the reduction in emissions is greater than the increase in consumption in B, that is if $K_t < \frac{D(c_B+\phi\delta+r_f)-D(c_B+r_f)}{\nu} + K_{Bi}$.

Case (e3) is similar to case (e2), with the subsidy rate capped at $s^I = \bar{s}_B$.

5.2 Carbon leakage

Carbon leakage occurs when there is an increase in greenhouse gas emissions in one country as a result of an emissions reduction by a second country with a stringent climate policy. Interestingly, in the power sector, leakage is constrained by the transmission capacity of the network. Therefore, expanding transmission has a risk of increasing carbon leakage.

What are the implications of the optimal climate policies on leakage risks? We define carbon leakage as the emission that would have occured within the jurisdiction in the absence of trade. For country A, leakage happens for any $K_t > 0$ under the assumption $c_A > c_B$. The level of leakage would thus depend on the level of K_t, as shown in Table 1.[10]

[10] See Appendix A.7 for detailed emissions level under the the second-best climate policies.

Table 1: Leakage comparison under different policy scenarios

Case	No policy	Uni-tax	Second-best policy
(a)	K_t	K_t	K_t
(b)	K_t	K_t	K_t
(c)	K_t	K_t	K_t
(d1)	K_t	K_t	$(1-\nu)K_t + \nu(Q_A - K_{Ai})$
(d2)	K_t	K_t	$(1-\nu)K_t + \nu(Q_A - K_{Ai})$
(e1)	K_t	K_t	$(1-\nu)K_t - \nu K_t$
(e2)	K_t	K_t	$(1-\nu)K_t - \nu K_{Bi}$
(e3)	K_t	K_t	$(1-\nu)K_t - \nu Q_B$

Table 1 shows that with a uni-tax (column three) does not add additional leakage risk for country A under the assumption $c_A > c_B$. However, by either limiting transmission or by adopting the second-best climate policies (column four), country A can reduce the leakage risk.[11]

[11] If, on the other hand, A has cost advantage in thermal power in the absence of a carbon tax $c_A < c_B$, carbon tax then imposes a leakage risk that can be dampened with a border tax or renewable subsidy. This result is straightforward if $c_A < c_B < \frac{r_i}{\nu}$. With no carbon tax, firms in country A invest only in thermal power and exports to country B. With a carbon tax higher than $c_B - c_A$, firms will import from country B up to the transmission capacity. Therefore, the leakage is K_t.

A Appendix

A.1 Optimal energy mix with constrained trade

Lemma 1 is solved by maximizing the joint welfare of the two countries when environmental damage reflects country A's tastes. Therefore, the social planner chooses the optimal consumption, production and capacity that maximize the joint welfare subject to the market equlibrium conditions. The maximization problem is as follows:

$$
\begin{aligned}
\max_{\substack{Q_j,K_{jf},q^h_{jf},K_{Ai},x^s\\ j\in\{A,B\},s\in\{h,l\}}} \quad & \sum_j S(Q_j) - (c_A+\delta)(\nu q^h_{Af} + (1-\nu)q^l_{Af}) - (c_B+\phi\delta)(\nu q^h_{Bf} \\
& + (1-\nu)q^l_{Bf}) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) - r_f(K_{Af}-K_{Bf}) \\
\text{s.t.} \quad & \bar{K}F(\tilde{r}_{Ai}) + q^h_{Af} - x^h = Q_A \\
& K_{Af} + x^l = Q_A \\
& q^h_{Bf} + x^h = Q_B \\
& K_{Bf} - x^l = Q_B \\
& 0 \le q^h_{jf} \le K_{jf} \quad \forall j \in \{A,B\} \\
& \tilde{r}_{Ai} \ge \underline{r}_i \\
& -K_t \le x^s \le K_t \quad \forall s \in \{s,h\}
\end{aligned}
\tag{A.1}
$$

The maximization problem can be simplified as

$$
\begin{aligned}
\max_{\substack{Q_j,x^s,\tilde{r}_{Ai}\\ j=A,B,s=h,l}} \quad & \sum_j S(Q_j) - \nu\big((c_A+\delta)(Q_A + x^h - \bar{K}F(\tilde{r}_{Ai})) + (c_B+\phi\delta)(Q_B - x^h)\big) \\
& - (1-\nu)\big((c_A+\delta)(Q_A - x^l) + (c_B+\phi\delta)(Q_B + x^l)\big) \\
& - r_f(Q_A+Q_B) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) \\
\text{s.t.} \quad & \bar{K}F(\tilde{r}_{Ai}) \le Q_A + x^h \qquad [\underline{\lambda}] \\
& x^h + x^l \le \bar{K}F(\tilde{r}_{Ai}) \qquad [\bar{\lambda}] \\
& x^h \le K_t \qquad [\bar{\mu}] \\
& x^h \ge -K_t \qquad [\underline{\mu}] \\
& x^l \le K_t \qquad [\xi] \\
& \tilde{r}_{Ai} \ge \underline{r}_i \qquad [\eta]
\end{aligned}
\tag{A.2}
$$

The Lagrangian is:

$$
\begin{aligned}
\mathcal{L} =& S(Q_A) + S(Q_B) - \nu\Big((c_A+\delta)(Q_A + x^h - \bar{K}F(\tilde{r}_{Ai})) + (c_B+\phi\delta)(Q_B - x^h) \\
&- \bar{\lambda}(\bar{K}F(\tilde{r}_{Ai}) - x^h - x^l) - \underline{\lambda}(Q_A + x^h - \bar{K}F(\tilde{r}_{Ai})) - \bar{\mu}(K_t - x^h) \\
&- \underline{\mu}(x^h + K_t) - \eta\bar{K}F(\tilde{r}_{Ai})\Big) \\
&- (1-\nu)\Big((c_A+\delta)(Q_A - x^l) + (c_B+\phi\delta)(Q_B + x^l) - \xi(K_t - x^l)\Big) \\
&- r_f(Q_A+Q_B) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i)
\end{aligned}
\tag{A.3}
$$

Taking the first order conditions:

$$
\frac{\partial \mathcal{L}}{\partial Q_A} = S'(Q_A) - c_A - \delta - r_f + \nu\underline{\lambda} = 0 \tag{A.4}
$$

$$
\frac{\partial \mathcal{L}}{\partial Q_B} = S'(Q_B) - c_B - \phi\delta - r_f = 0 \tag{A.5}
$$

$$
\frac{\partial \mathcal{L}}{\partial x^h} = -\nu(c_A - c_B + (1-\phi)\delta + \bar{\lambda} - \underline{\lambda} + \bar{\mu} - \underline{\mu}) = 0 \tag{A.6}
$$

$$
\frac{\partial \mathcal{L}}{\partial x^l} = (1-\nu)(c_A - c_B + (1-\phi)\delta - \xi) - \nu\bar{\lambda} = 0 \tag{A.7}
$$

$$
\frac{\partial \mathcal{L}}{\partial \tilde{r}_{Ai}} = \nu(c_A + \delta + \bar{\lambda} - \underline{\lambda} + \eta') - \tilde{r}_{Ai} = 0 \tag{A.8}
$$

where $\eta' = \frac{\eta'}{\bar{K}f(\tilde{r}_{Ai})}$ plus the complementary slackness conditions.

Rearranging equation A.8 we have

$$
\frac{\tilde{r}_{Ai}}{\nu} - (c_A + \delta) = \bar{\lambda} - \underline{\lambda} + \eta', \tag{A.9}
$$

and equations A.6 and A.8 give

$$
\frac{\tilde{r}_{Ai}}{\nu} - (c_B + \phi\delta) = \underline{\mu} - \bar{\mu} + \eta', \tag{A.10}
$$

By equation A.7, we have $c_A - c_B + (1-\phi)\delta = \xi + \frac{\nu}{1-\nu}\bar{\lambda}$. Since $c_A > c_B$ by assumption, then $\xi > 0$ and $\bar{\lambda} > 0$, so $x^l = K_t$. From equation A.6, we get that $Q_B = D(c_B + \phi\delta + r_f)$, $\forall K_t, \delta$.

Therefore, we only need to pin down Q_A, $\tilde{r}_{Ai}$, and x^h. Equation A.9 and A.10 jointly determine the threshold levels of SCC for renewable capacities and the direction of trade flow in state h. Consequently, all of the other choice variables can be pinned down through the value of the multipliers. Therefore, for each K_t, there exists a set of threshold δ, on which the optimal capacities, consumption levels, and trade quantities depend. Solving the focs, we obtain Lemma 1.

A.2 Optimal energy mix with interconnection and unlimited trade

If the transmission constraint is not binding, the maximization problem A.1 is modified by removing the transmission constraint. Therefore, the optimal level of prices and quantities are (denoted by superscript F)

(a) only thermal in country B: $\delta \leq \underline{\delta}^F$

$Q_A^F = Q_B^F = D(c_B + \phi\delta + r_f)$;

$K_{Bf}^F = q_{Bf}^{hF} = Q_A^F + Q_B^F$, $q_{Af}^{hF} = K_{Af}^F = 0$, $K_{Ai}^F = 0$;

$\underline{\delta}^F$ is such that $\phi\underline{\delta}^F = \frac{r_i}{\nu} - c_B$.

(b) renewable energy and thermal in state h: $\underline{\delta}^F < \delta \leq \bar{\delta}^F$

$Q_A^F = Q_B^F = D(c_B + \phi\delta + r_f)$;

$K_{Bf}^F = Q_A^F + Q_B^F$, $K_{Ai}^F = \bar{K}F(\nu(c_B + \phi\delta))$, $q_{Bf}^{hF} = K_{Bf}^F - K_{Ai}^F$, $q_{Af}^{hF} = K_{Af}^F = 0$;

$\bar{\delta}^F$ is defined by $\bar{K}F(\nu(c_B + \phi\bar{\delta}^F)) = Q_A^F + Q_B^F$.

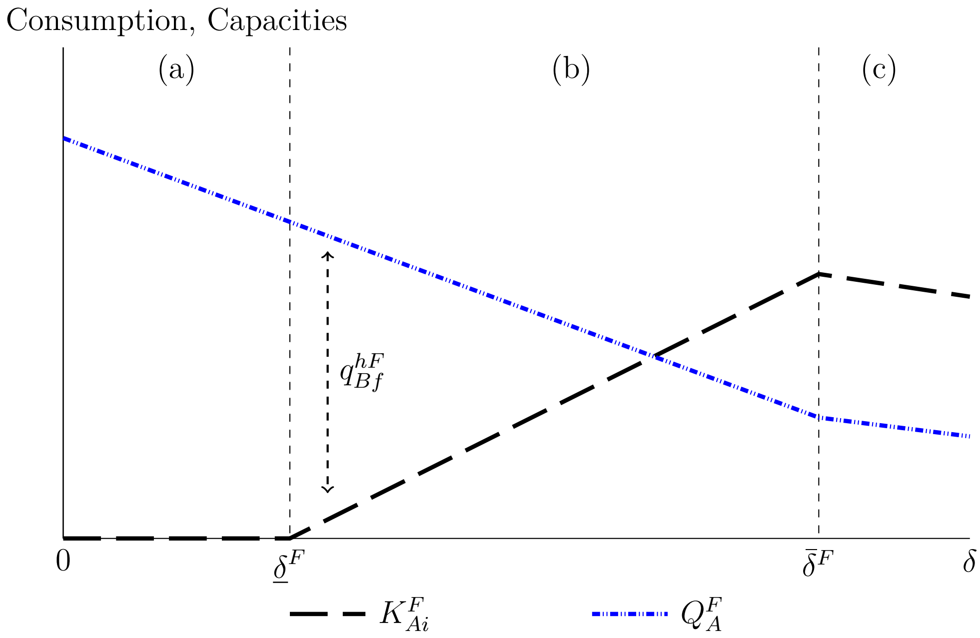
(c) renewable-energy-only in state h: $\delta > \bar{\delta}^F$

$Q_A^F = Q_B^F = D((1-\nu)(c_B + \phi\delta) + r_f + \tilde{r}_i^F)$;

$K_{Bf}^F = K_{Ai}^F = \bar{K}F(\tilde{r}_i^F) = Q_A^F + Q_B^F$, and $q_{Af}^{hF} = q_{Bf}^{hF} = K_{Af}^F = 0$.

This result is reminicent of Yang (2020, Lemma 2). Figure A.1 illustrates the optimal consumption and renewable capacity in country A as a function of the marginal damage/carbon tax.

Figure A.1: Optimal capacities and consumption in country A with no transmission constraint



A.3 Proof of Proposition 1

For the case of K_t binding, we separately analyze the following cases given different range of τ_A.

(a) $\tau_A < \frac{r_i}{\nu} - c_A$

$$W_A(\tau_A) = S(Q_A) - (c_A + r_f)(Q_A - K_t) - (c_B + r_f)K_t - \delta(Q_A - K_t + \phi(Q_B + K_t))$$

The the first order condition (foc) with respect to τ_A

$$\frac{\partial W_A}{\partial \tau_A} = \left(S'(Q_A) - c_A - \delta - r_f\right)\frac{\mathrm{d}Q_A}{\mathrm{d}\tau_A} \tag{A.11}$$

The optimal τ_A should be such that $S'(Q_A) - c_A - \delta - r_f = 0$. It is obvious that τ_A should be equal to δ for $\delta < \frac{r_i}{\nu} - c_A$.

(b) $\frac{r_i}{\nu} - c_A \leq \tau_A < \underline{\tau}_A$

$$\begin{aligned} W_A(\tau_A) =& S(Q_A) - (c_A + r_f)(Q_A - K_t) + \nu c_A \bar{K} F(\tilde{r}_{Ai}) - (c_B + r_f)K_t - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) \\ & - \delta(Q_A - K_t - \nu\bar{K}F(\tilde{r}_{Ai}) + \phi(Q_B + K_t)) \end{aligned}$$

The foc is

$$\frac{\partial W_A}{\partial \tau_A} = \left(S'(Q_A) - c_A - \delta - r_f\right)\frac{\mathrm{d}Q_A}{\mathrm{d}\tau_A} + \left(\nu(c_A+\delta) - \tilde{r}_{Ai}\right)\bar{K}F(\tilde{r}_{Ai})\frac{\mathrm{d}\tilde{r}_{Ai}}{\mathrm{d}\tau_A} \quad \text{(A.12)}$$

It is obvious that τ_A should be equal to δ for $\frac{r_i}{\nu} - c_A \leq \delta < \underline{\tau}_A$.

(c) $\underline{\tau}_A \leq \tau_A$

$$\begin{aligned} W_A(\tau_A) = & S(Q_A) - ((1-\nu)(c_A+\delta) + r_f)(Q_A - K_t) - (c_B + r_f)K_t - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) \\ & - \phi\delta(Q_B + K_t) \end{aligned}$$

The foc is

$$\frac{\partial W_A}{\partial \tau_A} = \left(S'(Q_A) - (1-\nu)(c_A+\delta) - r_f - \tilde{r}_{Ai})\right)\frac{\mathrm{d}Q_A}{\mathrm{d}\tau_A} \quad \text{(A.13)}$$

Thus, the second-best τ_A^t should satisfy

$$S'(Q_A) = (1-\nu)(c_A+\delta) + r_f + \tilde{r}_{Ai} \quad \text{(A.14)}$$

We can easily obtain that the optimal $\tau_A = \delta \ \forall \ \delta > \underline{\delta}_A$.

The analysis is straightforward when there is unlimited trade capacity. As the wholesale price is always lower in country B in the absence of a carbon tax, country A will not invest in any capacity and import only thermal power from country B. Therefore, the carbon tax in country A that is levied on production only does not have any effect on the amount of electricity consumed. Adjusting the carbon tax cannot increase local production or decrease emissions.

A.4 Proof of Proposition 2

To pin down the optimal level of the border tax given the levels of SCC, we separately analyze the four ranges of τ_x illustrated in Figure 3.

For binding transmission constraints:

i $\tau_x < \underline{\tau}_x$

A low level of BCA tax has no effect on the trade flow compare to just a uni-tax. As the uni-tax and the optimal production and consumption level are equivalent in country A if $\delta < \underline{\delta}_B$, there will be no need for a BCA tax in this range of SCC. Therefore, $\tau_A = \delta$ and $\tau_x = 0$ is optimal for $\delta < \underline{\delta}_B$.

ii $\underline{\tau}_x \leq \tau_x < \bar{\tau}_x$

A BCA tax in this range makes the transmission contraint binding only in state l ($0 < x_A^h < K_t, x_A^l = K_t$). The welfare is thus

$$\begin{aligned} W_A =& S(Q_A) - ((1-\nu)(c_A+\delta)+r_f)(Q_A - K_t) - \bar{K}\int_{\underline{r}_i}^{\nu(c_B+\tau_x)} r_i dF(r_i) \\ & - \nu c_B(Q_A - K_{Ai}) - ((1-\nu)c_B + r_f)K_t \\ & - \phi\delta(Q_B + (1-\nu)K_t + \nu(Q_A - K_{Ai})) \end{aligned} \tag{A.15}$$

$$\begin{aligned} \max_{\tau_A,\,\tau_x} \quad & W_A \\ \text{s.t.} \quad & Q_A = D((1-\nu)(c_A+\tau_A) + \nu(c_B+\tau_x) + r_f) \\ & K_{Ai} = \bar{K}F(\nu(c_B+\tau_x)) \end{aligned} \tag{A.16}$$

The optimal τ_A and τ_x should satisfy

$$S'(Q_A) = (1-\nu)(c_A+\delta) + \nu(c_B+\phi\delta) + r_f \tag{A.17}$$

$$\tau_x = \phi\delta \tag{A.18}$$

Therefore, $\tau_A = \delta$ and $\tau_x = \phi\delta$. As $\underline{\tau}_x \leq \tau_x < \bar{\tau}_x$, the δ that satisfies this range is $\underline{\delta}_B \leq \delta < \mathring{\delta}$. $\mathring{\delta}$ is such that $\bar{K}F(\nu(c_B+\phi\mathring{\delta})) = D((1-\nu)(c_A+\mathring{\delta}) + \nu(c_B+\phi\mathring{\delta}) + r_f)$. The equilibrium consumption level in country A is thus equivalent as that in the optimal case.

iii $\bar{\tau}_x \leq \tau_x < c_A - c_B + \tau_A$

A BCA tax in this range means there is import only in state l up to the transmission constraint ($x_A^h = 0, x_A^l = K_t$). The welfare level is thus:

$$\begin{aligned} W_A =& S(Q_A) - ((1-\nu)(c_A+\delta)+r_f)(Q_A - K_t) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) \\ & - ((1-\nu)c_B + r_f)K_t - \delta\phi(Q_B + (1-\nu)K_t) \end{aligned} \tag{A.19}$$

$$\begin{aligned} \max_{\tau_A,\,\tau_x} \quad & W_A \\ \text{s.t.} \quad & Q_A = D((1-\nu)(c_A+\delta) + r_f + \tilde{r}_{Ai}) \\ & K_{Ai} = Q_A \end{aligned} \tag{A.20}$$

In this case, the optimal $\tau_A = \delta$ and τ_x can be any value in the range $[\tilde{\tau}_x, c_A - c_B + \tau_A)$.

If $\delta > \mathring{\delta}$, a BCA tax in this range would increase welfare compare to with only a carbon tax.

iv $\tau_x \geq c_A - c_B + \tau_A$

A BCA tax in this range will limit trade in both states. This is equivalent as reducing transmission capacity to zero. In this case, the optimal $\tau_A = \delta$ so the consumption and production level in A are the same as the no interconnection case. However, since country A can benefit from importing thermal power at a lower cost, it is not optimal to limit trade.

For non-binding transmission constraint:

i $\tau_x < \underline{\tau}_x^F$

In both states, A imports from B the thermal power equals to their demand ($x^s = Q_A$).

$$\begin{aligned} W_A = &S(Q_A) - p_B Q_A - \delta\phi(Q_A + Q_B) \\ \text{s.t.} \quad &S'(Q_A) = p_B + \tau_x \end{aligned} \tag{A.21}$$

In this case, the optimal $\tau_x = \phi\delta$. Since the incentive compatitibility requires that $c_A + \tau_A + r_f > c_B + r_f + \tau_x$, thus the optimal $\tau_A > c_B - c_A + \phi\delta$. If $\delta < \underline{\delta}^F$ (defined in Appendix A.2), then such τ_x is optimal.

ii $\underline{\tau}_x^F \leq \tau_x < \bar{\tau}_x^F$

In state l, A imports from B full demand, and in state h, A uses renewable capacity to satisfy partial demand.

$$\begin{aligned} W_A = &S(Q_A) - p_B^h(Q_A - K_{Ai}) - \bar{K}\int_{\underline{r}_i}^{\nu(c_B+\tau_x)} r_i dF(r_i) \\ &- \delta(K_{Ai} + \phi(Q_A - K_{Ai} + Q_B)) \\ \text{s.t.} \quad &S'(Q_A) = p_B + \tau_x \end{aligned} \tag{A.22}$$

In this case, the optimal $\tau_x = \phi\delta$. Since the incentive compatibility requires that $c_A + \tau_A > \frac{\tilde{r}_{Ai}}{\nu} = c_B + \tau_x$, thus the optimal $\tau_A > c_B - c_A + \phi\delta$. If $\delta < \mathring{\delta}^F$, then such τ_x is optimal. $\mathring{\delta}^F$ is such that $\bar{K}F(\nu(c_B + \phi\mathring{\delta}^F)) = D(c_B + r_f + \phi\mathring{\delta}^F)$.

iii $\bar{\tau}_x^F \leq \tau_x < c_A - c_B + \tau_A$

In state l, A imports from B full demand, and in state h, A uses only renewable capacity to satisfy demand.

$$
\begin{aligned}
W_A =& S(Q_A) - ((1-\nu)c_B + r_f)Q_A - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) \\
& - \delta\phi(Q_B + (1-\nu)Q_A)
\end{aligned} \tag{A.23}
$$

$$
\begin{aligned}
\max_{\tau_A,\,\tau_x} \quad & W_A \\
\text{s.t.} \quad & Q_A = D((1-\nu)(c_B+\tau_x) + r_f + \tilde{r}_{Ai}) \\
& K_{Ai} = Q_A
\end{aligned} \tag{A.24}
$$

The optimal $\tau_x = \phi\delta$ and $\tau_A > c_B - c_A + \phi\delta$. If $\delta \geq \mathring{\delta}^F$, then such τ_x and τ_A are optimal.

iv $\tau_x \geq c_A - c_B + \tau_A$

This is equivalent as the no interconnection case. In this case, the optimal $\tau_A = \delta$.

A.5 Proof of Proposition 3

A.5.1 Binding transmission constraint

i $s < \underline{s}$

With subsidy in this range, the renewable capacity is not enough to cover demand in state h. $p_A^h = c_B + \tau_x = \frac{\tilde{r}_{Ai} - s}{\nu}$. $p_A = (1-\nu)(c_A + \tau_A) + \nu(c_B + \tau_x) + r_f$. The welfare level:

$$
\begin{aligned}
W_A =& S(Q_A) - ((1-\nu)(c_A+\delta) + r_f)(Q_A - K_t) - \bar{K}\int_{\underline{r}_i}^{\nu(c_B+\tau_x)+s} r_i dF(r_i) \\
& - \nu c_B(Q_A - \bar{K}F(\nu(c_B+\tau_x)+s)) - ((1-\nu)c_B + r_f)K_t \\
& - \phi\delta(Q_B + (1-\nu)K_t + \nu(Q_A - \bar{K}F(\nu(c_B+\tau_x)+s)))
\end{aligned} \tag{A.25}
$$

It is obvious that the welfare level is the same as equation A.15 when $s = 0$. Therefore, a subsidy is not needed for $\delta < \mathring{\delta}$.

ii $\underline{s} \leq s < \bar{s}$

With a subsidy in this range, the country A has excess renewable capacity for export in state h. For country B to be willing to import, the after-subsidy unit price need to be weakly lower than c_B. Assume that country B imports if they are indifferent, i.e. if export price equals c_B.

$p_A^h = c_B = \frac{\tilde{r}_{Ai}-s}{\nu}$. $p_A = (1-\nu)(c_A+\tau_A)+\nu c_B + r_f$. The welfare level:

$$
\begin{aligned}
W_A =& S(Q_A) - ((1-\nu)(c_A+\delta)+r_f)(Q_A-K_t) - \bar{K}\int_{\underline{r}_i}^{\nu c_B+s} r_i dF(r_i) \\
&- \nu c_B(Q_A - \bar{K}F(\nu c_B+s)) - ((1-\nu)c_B+r_f)K_t \\
&- \phi\delta(Q_B+(1-\nu)K_t - \nu(\bar{K}F(\nu c_B+s)-Q_A))
\end{aligned} \tag{A.26}
$$

The social planner chooses the optimal τ_A, τ_x, and s subject to the government budget constraint.

$$
\begin{aligned}
\max_{\tau_A,\tau_x,s} \quad & W_A \\
\text{s.t.} \quad & Q_A = D((1-\nu)(c_A+\tau_A)+\nu c_B+r_f) \\
& (1-\nu)(\tau_A(Q_A-K_t)+\tau_x K_t) \geq s\bar{K}F(\nu c_B+s)
\end{aligned} \tag{A.27}
$$

The optimal $\tau_A = (\delta + \frac{\nu\phi\delta}{1-\nu})\frac{1}{1-\mu(1-\frac{1}{\varepsilon_{Q\tau}})}$, where μ is the Lagrangian multiplier for the budget constraint and $\varepsilon_{Q\tau} = \frac{dQ_A}{Q_A}/\frac{d\tau_A}{\tau_A}$ is the elasticity of consumption with respect to the carbon tax. $s = \frac{\phi\delta\nu-\mu\frac{F}{f}}{1+\mu}$, τ_x is such that minimize $\frac{\partial\mathcal{L}}{\partial\tau_x} = \mu(1-\nu)K_t$.

(a) $\mu = 0$

If the budget constraint is not binding, the optimal $\tau_A = \delta(1+\phi\frac{\nu}{1+\nu})$, $\tau_x = 0$ and $s = \nu\phi\delta$.

(b) $\mu > 0$

If the budget constraint is binding, τ_x can be used to adjust the tax revenue, as long as $\tau_x < c_A - c_B + \tau_A$. In this case, τ_A and s can be maintained at the non-binding rate.

The optimal s within the range of $[\underline{s}, \bar{s}]$ is when $\mathring{\delta} < \delta < \bar{\delta}$. Note here that since the subsidy decreases the wholesale price in state h, in order to avoid excess consumption, the carbon tax rate is increased by $\frac{\phi\nu}{1-\nu}\delta$. This increase offsets the decrease in expected retail price from the subsidy.

iii $s \geq \bar{s}$

For a subsidy rate in this range, $p_A^h = \frac{\tilde{r}_{Ai}-s}{\nu}$ and $p_A = (1-\nu)(c_A+\tau_A)+\tilde{r}_{Ai}-s+r_f$. Note that since capacity is costly, it is inefficient to have renewable capacity greater than Q_A+K_t. Thus, there is no need for $s > \bar{s}$. Thus $s = \bar{s}$ such that $K_{Ai} = \bar{K}F(\nu c_B+\bar{s}) = Q_A+K_t$.

$$
\begin{aligned}
W_A =& S(Q_A) - ((1-\nu)(c_A+\delta)+r_f)(Q_A-K_t) - \bar{K}\int_{\underline{r}_i}^{\nu c_B+\bar{s}} r_i dF(r_i) \\
&+ \nu c_B K_t - ((1-\nu)c_B+r_f)K_t - \phi\delta(Q_B+(1-2\nu)K_t)
\end{aligned} \tag{A.28}
$$

Optimal τ_A and τ_x are solve by maximizing the social welfare function subject to the government budget constraint.

$$\begin{aligned}
\max_{\tau_A, \tau_x} \quad & W_A \\
\text{s.t.} \quad & Q_A = D((1-\nu)(c_A+\tau_A)+r_f+\nu c_B) \\
& (1-\nu)(\tau_A(Q_A-K_t)+\tau_x K_t) \geq \bar{s}(Q_A+K_t) \\
& \bar{K}F(\nu c_B+\bar{s}) = Q_A+K_t
\end{aligned} \tag{A.29}$$

(a) $\mu = 0$

If the budget constraint is not binding, the optimal $\tau_A = \delta + \frac{\bar{s}}{1-\nu}$ and $\tau_x = 0$. $\bar{s}$ decreases in δ.

(b) $\mu > 0$

If the budget constraint is binding, we can find a $\tau_x \in [0, c_A - c_B + \tau_A]$ such that the budget is balanced.

$s = \bar{s}$ is optimal for $\delta > \bar{\delta}$.

A special case is that K_t is not binding for importing in state l but is binding for exporting in state h. $p_A^h = \frac{\tilde{r}_{Ai}-s}{\nu}$, $p_A^l = c_B + \tau_x + \frac{r_f}{1-\nu}$ and $p_A = (1-\nu)(c_B+\tau_x) + \nu c_B + r_f$.

$$\begin{aligned}
W_A = & S(Q_A) - \bar{K}\int_{\underline{r}_i}^{\nu c_B+\bar{s}} r_i dF(r_i) \\
& + \nu c_B K_t - ((1-\nu)c_B + r_f)Q_A - \phi\delta(Q_B + (1-\nu)Q_A - \nu K_t)
\end{aligned} \tag{A.30}$$

$$\begin{aligned}
\max_{\tau_x} \quad & W_A \\
\text{s.t.} \quad & Q_A = D((1-\nu)(c_B+\tau_x)+\nu c_B+r_f) \\
& (1-\nu)\tau_x Q_A \geq \bar{s}(Q_A+K_t) \\
& \bar{K}F(\nu c_B+\bar{s}) = Q_A+K_t
\end{aligned} \tag{A.31}$$

(a) $\mu = 0$

If the budget constraint is not binding, the optimal $\tau_A > c_B - c_A + \tau_x$ and $\tau_x = \phi\delta + \frac{\bar{s}}{1-\nu}$. $\bar{s}$ decreases in δ.

(b) $\mu > 0$

If the budget constraint is binding, $\tau_x = \frac{\phi\delta + \frac{1+\mu}{1-\nu}\bar{s} + \mu\frac{Q_A}{\bar{K}f(\nu c_B+\bar{s})}}{(1-\nu)(1+\mu(1+\frac{1}{\varepsilon_{Q\tau_x}}))}$, where $\varepsilon_{Q\tau_x}$ is the elasticity of Q_A with respect to τ_x.

A.5.2 Non-binding transmission constraint

i $s < \underline{s}^F$

If the transmission constraint is not binding for either states of nature, for $\delta < \mathring{\delta}^F$, the combination of a carbon tax and a BCA tax can be sufficient to restore the optimal production and consumption in country A. There is no need for a subsidy rate lower than $\underline{s}^F$ ($\underline{s}^F = \tilde{r}_{Ai}(Q_A) - \nu c_B$).

ii $\underline{s}^F \leq s < \bar{s}^F$

$\bar{s}^F = \tilde{r}_{Ai}(Q_A + Q_B) - \nu c_B$, $p_A^h = c_B = \frac{\tilde{r}_{Ai} - s}{\nu}$. $p_A = (1-\nu)(c_B + \tau_x) + \nu c_B + r_f$. The welfare level:

$$\begin{aligned} W_A =& S(Q_A) - \bar{K}\int_{\underline{r}_i}^{\nu c_B + s} r_i dF(r_i) \\ &+ \nu c_B(\bar{K}F(\nu c_B + s) - Q_A) - ((1-\nu)c_B + r_f)Q_A \\ &- \phi\delta(Q_B + (1-\nu)Q_A - \nu(\bar{K}F(\nu c_B + s) - Q_A)) \end{aligned} \tag{A.32}$$

The social planner chooses the optimal τ_A, τ_x, and s subject to the government budget constraint.

$$\begin{aligned} \max_{\tau_A, \tau_x, s} \quad & W_A \\ \text{s.t.} \quad & Q_A = D((1-\nu)(c_B + \tau_x) + \nu c_B + r_f) \\ & (1-\nu)\tau_x Q_A \geq s\bar{K}F(\nu c_B + s) \end{aligned} \tag{A.33}$$

The optimal $\tau_x = \frac{\phi\delta}{1-\nu}\frac{1}{1+\mu(1+\frac{1}{\varepsilon_{K\tau_x}})}$, $s = \frac{\phi\delta\nu - \mu\frac{F}{f}}{1+\mu}$, and $\tau_A > c_B - c_A + \tau_x$. Unlike the binding transmission case, here the use of the carbon tax is just to make sure that within country A, production is shifted towards renewables. The BCA tax is needed to garantee in state h, thermal power from country B is less competitive compared to the renewables of A.

(a) $\mu = 0$

$\tau_x = \frac{\phi\delta}{1-\nu}$, $s = \phi\delta\nu$

(b) $\mu > 0$

By pluging τ_x in the budget constraint, we can obtain a unique set of s and τ_x.

iii $s \geq \bar{s}^F$

With a high subsidy rate, renewable capacity covers consumption in both country A and B in state h. The higher the subsidy rate, the lower wholesale prices in state

h in both countries. $p_A^h = p_B^h = \frac{\tilde{r}_{Ai}-s}{\nu} \leq c_B$, $p_A = (1-\nu)(c_B+\tau_x)+\tilde{r}_{Ai}-s+r_f$, and $p_B = (1-\nu)c_B + \tilde{r}_{Ai} - s + r_f$.

The welfare is:

$$\begin{aligned} W_A =& S(Q_A) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) + (\tilde{r}_{Ai}-s)Q_B \\ &- ((1-\nu)c_B + r_f)Q_A - \phi\delta(1-\nu)(Q_B+Q_A) \end{aligned} \tag{A.34}$$

Optimal τ_x, and s are solve by maximizing the social welfare function subject to the government budget constraint and the production constraints.

$$\begin{aligned} \max_{\tau_x,\, s} \quad & W_A \\ \text{s.t.} \quad & Q_A = D((1-\nu)(c_B+\tau_x)+\tilde{r}_{Ai}-s+r_f) \\ & Q_B = D((1-\nu)c_B+\tilde{r}_{Ai}-s+r_f) \\ & (1-\nu)\tau_x Q_A \geq s(Q_A+Q_B) \\ & \bar{K}F(\tilde{r}_{Ai}) = Q_A + Q_B \end{aligned} \tag{A.35}$$

Proof. Lagrangian:

$$\begin{aligned} \mathcal{L} =& S(Q_A) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) + (\tilde{r}_{Ai}-s)Q_B \\ &- ((1-\nu)c_B + r_f)Q_A - \phi\delta(1-\nu)(Q_B+Q_A) \\ &+ \mu(1-\nu)\tau_x Q_A - \mu s(Q_A+Q_B) \end{aligned} \tag{A.36}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \tau_x} =& (S'(Q_A) - (1-\nu)(c_B+\phi\delta) - r_f + \mu(1-\nu)\tau_x - \mu s)\frac{\partial Q_A}{\partial \tau_x} \\ &+ (-\bar{K}f(\tilde{r}_{Ai})\tilde{r}_{Ai} + Q_B)\frac{\partial \tilde{r}_{Ai}}{\partial \tau_x} \\ &+ ((\tilde{r}_{Ai} - s - \phi\delta(1-\nu) - \mu s)\frac{\partial Q_B}{\partial \tau_x} \\ &+ \mu(1-\nu)Q_A \\ \frac{\partial \mathcal{L}}{\partial s} =& (S'(Q_A) - (1-\nu)(c_B+\phi\delta) - r_f + \mu(1-\nu)\tau_x - \mu s)\frac{\partial Q_A}{\partial s} \\ &+ ((\tilde{r}_{Ai} - s - \phi\delta(1-\nu) - \mu s)\frac{\partial Q_B}{\partial s} \\ &+ (-\bar{K}f(\tilde{r}_{Ai})\tilde{r}_{Ai} + Q_B)\frac{\partial \tilde{r}_{Ai}}{\partial s} \\ &- Q_B - \mu(Q_A+Q_B) \end{aligned}$$

where $\frac{\partial \tilde{r}_{Ai}}{\partial \tau_x} = \frac{(1-\nu)D'_A}{\bar{K}f - D'_A - D'_B} < 0$ (by the implicit function theorem), $\frac{\partial Q_A}{\partial \tau_x} = D'_A((1-\nu) + \frac{\partial \tilde{r}_{Ai}}{\partial \tau_x}) < 0$, $\frac{\partial Q_B}{\partial \tau_x} = D'_B \frac{\partial \tilde{r}_{Ai}}{\partial \tau_x} > 0$;

$\frac{\partial \tilde{r}_{Ai}}{\partial s} = \frac{D'_A + D'_B}{D'_A + D'_B - \bar{K}f} \in (0,1)$, $\frac{\partial Q_A}{\partial s} = D'_A(\frac{\partial \tilde{r}_{Ai}}{\partial s} - 1) > 0$, $\frac{\partial Q_B}{\partial s} = D'_B(\frac{\partial \tilde{r}_{Ai}}{\partial s} - 1) > 0$.

By solving the focs, we obtain a unique set of τ_x and s. □

A.6 Proof of Proposition 4

i $s < \underline{s}_B$

A subsidy in this range will not illicite any renewable capacity investment in country B. When $\delta < \mathring{\delta}$, $s = 0$ is the optimal choice for country A.

ii $\underline{s}_B \leq s < \bar{s}_B$

The renewable capacity in B is up to $K_{Bi} = \bar{K}(F(\nu c_B + s) - F(\tilde{r}_{Ai}))$, $p_B^h = c_B$.

The social welfare of A related to the subsidy in this case is

$$\begin{aligned} W_A =& S(Q_A) - ((1-\nu)(c_A + \delta) + r_f)(Q_A - K_t) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_{Ai}} r_i dF(r_i) \\ &+ \theta(\nu c_B K_{Bi} - \bar{K}\int_{\tilde{r}_{Ai}}^{\nu c_B + s} r_i dF(r_i)) \\ &- ((1-\nu)c_B + r_f)K_t - \phi\delta(Q_B + (1-\nu)K_t - \nu K_{Bi}) \end{aligned} \tag{A.37}$$

$$\begin{aligned} \max_{\tau_A, \tau_x, s} \quad & W_A \\ \text{s.t.} \quad & Q_A = D((1-\nu)(c_A + \tau_A) + \tilde{r}_{Ai} + r_f) \\ & K_{Bi} = \bar{K}(F(\nu c_B + s) - F(\tilde{r}_{Ai})) \\ & (1-\nu)(\tau_A(Q_A - K_t) + \tau_x K_t) \geq sK_{Bi} \end{aligned} \tag{A.38}$$

It is straight forward that the subsidy rate has no effect over the production and consumption level in A. So the optimal choice of τ_A and τ_x can be consistent with that in section 4, where $\tau_A = \delta$ and $\tau_x \in [\bar{\tau}_x, c_A - c_B + \delta)$.

The maximization problem can be simplified as the following:

$$\begin{aligned} \max_{s} \quad & \theta(\nu c_B K_{Bi} - \bar{K}\int_{\tilde{r}_{Ai}}^{\nu c_B + s} r_i dF(r_i)) + \phi\delta\nu K_{Bi} \\ \text{s.t.} \quad & K_{Bi} = \bar{K}(F(\nu c_B + s) - F(\tilde{r}_{Ai})) \end{aligned} \tag{A.39}$$

$$\frac{\partial W_A}{\partial s} = (\theta\nu c_B + \phi\delta)\nu - (\nu c_B + s) = 0 \tag{A.40}$$

The optimal $s = \nu((\theta-1)c_B + \phi\delta)$. If $\theta = 1$, then the subsidy rate is equivalent to the domestic subsidy case, whereas if $\theta < 1$, the subsidy rate is lower than the domestic rate. However, it is only true for $K_{Bi} < K_t$. For any given level of transmission capacity, domestic renewable capacity is bounded by K_t, but international capacity can exceed the limit. Intuitively, the less integrated the two markets (lower K_t), the better it is to offer international subsidy.

This range of subsidy is optimal if $\delta < \delta^I$, where δ^I satisfies $\bar{K}(F(\theta\nu c_B + \phi\delta^I)\nu) - F(\tilde{r}_{Ai})) = D(c_B + r_f)$, and $\delta^I > \bar{\delta}$.

iii $s \geq \bar{s}_B$

The renewable capacity in B is capped at $K_{Bi} = Q_B$. Increasing the subsidy rate will decrease the wholesale price in country B as $p_B^h = \frac{\tilde{r}_{Bi}-s}{\nu}$ and $p_B = (1-\nu)c_B + r_f + \tilde{r}_{Bi} - s$.

$$\begin{aligned} \max_{s} \quad & \theta((\tilde{r}_{Bi} - s)Q_B - \bar{K}\int_{\tilde{r}_{Ai}}^{\tilde{r}_{Bi}} r_i dF(r_i)) - \phi\delta(1-\nu)Q_B \\ \text{s.t.} \quad & Q_B = \bar{K}(F(\tilde{r}_{Bi}) - F(\tilde{r}_{Ai})) \\ & Q_B = D((1-\nu)c_B + r_f + \tilde{r}_{Bi} - s) \end{aligned} \tag{A.41}$$

$$\frac{\partial W_A}{\partial s} = \theta(\frac{\partial \tilde{r}_{Bi}}{\partial s} - 1)Q_B + (\theta(\tilde{r}_{Bi} - s) - \phi\delta(1-\nu))\frac{\partial Q_B}{\partial s} - \theta\bar{K}f(\tilde{r}_{Bi})\tilde{r}_{Bi}\frac{\partial \tilde{r}_{Bi}}{\partial s} \tag{A.42}$$

where $\frac{\partial \tilde{r}_{Bi}}{\partial s} = \frac{D'}{D'-\bar{K}f(\tilde{r}_{Bi})} \in (0,1)$ and $\frac{\partial Q_B}{\partial s} = D'(\frac{\partial \tilde{r}_{Bi}}{\partial s} - 1) > 0$. Simplifying equation A.42, we can obtain

$$\frac{\partial W_A}{\partial s} = \theta(\frac{\partial \tilde{r}_{Bi}}{\partial s} - 1)Q_B - (\theta s + \phi\delta(1-\nu))\frac{\partial Q_B}{\partial s} < 0 \tag{A.43}$$

The about relationship holds true for any θ and ϕ. Therefore, we want the minimum value of s, which given the range equals $\bar{s}_B$. For $\delta \geq \delta^I$, an international subsidy rate in this range is optimal.

Figure 8 illustrates Proposition 4. Comparing the total renewable capacity of a domestic and international subsidy, we have the following three cases:

(a) If $\delta \in [\mathring{\delta}, \delta^e)$, domestic subsidy results in a higher subsidy rate, and in turn higher renewable capacity than with an international subsidy. δ^e denotes the thershold SCC such that the total renewable capacity under the two subsidy schemes are equivalent. Note that $\delta^e = \bar{\delta}$ if $\theta = 1$. The lower θ, the further δ^e moves to the right. Therefore, if country A obtains a lower share of the investment profit, it can obtain a higher renewable capacity if the government subsidize firms for local capacity and export directly electricity.

(b) If $\delta^e \leq \delta < \delta^I$, international subsidy results in a total higher renewable capacity. This is because the renewable capacity that generates electricity for country B's consumption is no longer constrained by the transmission capacity. Country A thus benefits from the further reduction in environmental damage and investment return. Note that the smaller K_t, the more δ^e is to the left, which indicates higher benefit of international subsidy for a given level of SCC.

(c) If $\delta \geq \delta^I$, the subsidy rate should be the minimum level such that country B produce with only renewable capacity in state h.

A.7 Carbon emissions under optimal climate policy

Table 1 follows directly from the emission level listed below.

Table A.1: Emissions in each jurisdiction under the second-best carbon policies

Case	E_A	E_B
(a)	$D(c_A + \delta + r_f) - K_t$	$D(c_B + r_f) + K_t$
(b)	$D(c_A + \delta + r_f) - \nu\bar{K}F(\nu(c_A + \delta)) - K_t$	$D(c_B + r_f) + K_t$
(c)	$(1-\nu)(D((1-\nu)(c_A + \delta) + r_f + \tilde{r}_{Ai}) - K_t)$	$D(c_B + r_f) + K_t$
(d1)	$(1-\nu)(D((1-\nu)(c_A + \delta) + r_f + \nu(c_B + \phi\delta)) - K_t)$	$D(c_B + r_f) + (1-\nu)K_t$ $+\nu(D((1-\nu)(c_A + \delta) + r_f + \nu(c_B + \phi\delta))$ $-\bar{K}F(\nu(c_B + \phi\delta)))$
(d2)	$(1-\nu)(D((1-\nu)(c_A + \delta) + r_f + \nu(c_B + \phi\delta)) - K_t$	$D(c_B + r_f) + (1-\nu)K_t$ $+\nu(D((1-\nu)(c_A + \delta) + r_f + \nu(c_B + \phi\delta))$ $-\bar{K}F(\nu(c_B + \phi\delta)))$
(e1)	$(1-\nu)(D((1-\nu)(c_A + \delta) + r_f + \nu c_B + \bar{s}) - K_t)$	$D(c_B + r_f) + (1-\nu)K_t - \nu K_t$
(e2)	$(1-\nu)(D((1-\nu)(c_A + \delta) + r_f + \tilde{r}_{Ai}) - K_t)$	$D(c_B + r_f) + (1-\nu)K_t$ $-\nu\bar{K}(F(\nu(\theta c_B + \phi\delta)) - F(\tilde{r}_{Ai}))$
(e3)	$(1-\nu)(D((1-\nu)(c_A + \delta) + r_f + \tilde{r}_{Ai}) - K_t)$	$(1-\nu)(D(c_B + r_f) + K_t)$

References

Ambec, S., & Crampes, C. (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics*, *34*(3), 319–336.

Ambec, S., & Crampes, C. (2019). Decarbonizing electricity generation with intermittent sources of energy. *Journal of the Association of Environmental and Resource Economists*, *6*(6), 919–948.

Böhringer, C., Bye, B., Fæhn, T., & Rosendahl, K. E. (2017). Targeted carbon tariffs: Export response, leakage and welfare. *Resource and Energy Economics*, *50*, 51–73.

Böhringer, C., Fischer, C., & Rosendahl, K. E. (2014). Cost-effective climate policy design: Size matters. *Journal of the Environmental Economics and Management*, *67*(3), 318–339.

Böhringer, C., Rosendahl, K. E., & Storrøsten, H. B. (2017). Robust policies to mitigate carbon leakage. *Journal of Public Economics*, *149*, 35–46.

Chen, Y. (2009). Does a regional greenhouse gas policy make sense? a case study of carbon leakage and emissions spillover. *Energy Economics*, *31*(5), 667–675.

Dissou, Y., & Eyland, T. (2011). Carbon control policies, competitiveness, and border tax adjustments. *Energy Economics*, *33*(3), 556–564.

European Commission. (2018). *Towards a sustainable and integrated europe: Report of the commission expert group on electricity interconnection targets*. European Commission.

Fischer, C., & Fox, A. K. (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management*, *64*(2), 199–216.

Fowlie, M. L. (2009). Incomplete environmental regulation, imperfect competition, and emissions leakage. *American Economic Journal: Economic Policy*, *1*(2), 72–112.

Helm, C., & Mier, M. (2019). On the efficient market diffusion of intermittent renewable energies. *Energy Economics*, *80*, 812–830.

MacDonald, A. E., Clack, C. T., Alexander, A., Dunbar, A., Wilczak, J., & Xie, Y. (2016). Future cost-competitive electricity systems and their impact on US CO_2 emissions. *Nature Climate Change*, *6*(5), 526.

Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics*, *5*(1), 15–29.

Martin, R., Muûls, M., De Preux, L. B., & Wagner, U. J. (2014). Industry compensation under relocation risk: A firm-level analysis of the eu emissions trading scheme. *American Economic Review*, *104*(8), 2482–2508.

Prete, C. L., Tyagi, A., & Hohl, C. (2019). California's cap-and-trade program and emission leakage in the electricity sector: An empirical analysis. *Working Paper*.

Sauma, E. (2012). The impact of transmission constraints on the emissions leakage under cap-and-trade program. *Energy policy*, *51*, 164–171.

Yang, Y. (2020). Electricity interconnection with intermittent renewables. *TSE working paper*, *20-1075*.