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“Climate policy with electricity trade”

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Abstract

Trade reduces the effectiveness of climate policies such as carbon pricing when domestic products are replaced by more carbon-intensive imports. We investigate the impact of unilateral carbon pricing on electricity generation in a country open to trade through interconnection lines. We characterize the energy mix with intermittent renewable sources of energy (wind or solar power). Electricity trade limits the penetration of renewables due to trade-induced competition. A carbon border adjustment mechanism (CBAM) removes this limit by increasing the cost of imported power, or by deterring imports. The CBAM must be complemented by a subsidy on renewables to increase renewable generation above domestic consumption. The interconnection line is then used to export power rather than importing it when renewables are producing. We also examine network pricing and investment into interconnection capacity. A higher carbon price increases interconnection investment which further reduces the effectiveness of carbon pricing. In contrast, when renewable electricity is exported, a higher subsidy on renewables reduces further carbon emissions by expanding interconnection capacity.

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

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

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1 Introduction

Electricity interconnection has been promoted in many countries as a means to enhance energy efficiency and security, while also facilitating the diffusion of renewable energy to areas lacking the requisite technology or natural resources.[1] Interconnection indeed presents a viable solution to combat renewable intermittency, especially if the interconnected zones have negatively correlated renewable generation or peak demands. Additionally, it can help mitigate carbon emissions, provided that the interconnected countries implement coordinated carbon policies at appropriate levels (Yang 2022). However, most countries or regions lack homogeneous carbon policies.[2] For instance, California has implemented a cap-and-trade system for carbon emissions from power generation while being interconnected with states in the western United States that have not instituted any carbon policies. Consequently, carbon emissions from electricity consumed in California leak outside the state's borders, with the leakage rate estimated at 70% (Prete et al. 2019).

To address carbon leakage, the European Union (EU) has recently adopted a Carbon Border Adjustment Mechanism (CBAM) for the power sector. Electricity importers are now required to pay a tariff calculated based on the emission factor of the imported kilowatt-hours (kWh), multiplied by the price of emission allowances in the EU's Emission Trading Scheme (ETS). Importers are to submit the emission factor annually, with certification from a third party. In the absence of this submission, a default emission factor will be applied (Ambec 2022). When carbon emissions are priced in the country of origin, only the price difference relative to the European price will be charged. In practice, the CBAM on electricity primarily affects countries connected to the EU's grid. Some of these countries are already part of the EU ETS (e.g., Norway, Liechtenstein), or have implemented their own ETS (e.g., Switzerland, the UK). However, others do not price carbon emissions at all (e.g., Albania, Morocco, Russia, Serbia, Turkey) and, as such, will be subject to the carbon tariff under the CBAM.[3] A policy similar to the CBAM has been in place in California since 2013. Nevertheless, research indicates that resource reshuffling continues to result in substantial leakage to unregulated regions (Fowlie et al. 2021).

We investigate climate policies for power generation in the context of limited electricity interconnection. Specifically, we examine the extent to which various market-based instruments (carbon pricing, carbon border adjustment mechanisms, and renewable sub-

[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) simulated that a national grid system in the United States has the potential to reduce its carbon dioxide emissions by up to 80% relative to 1990 levels.

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

[3] Information regarding interconnections with the EU's grid can be found in European Union 2019.

sidies) can effectively reduce emissions from electricity generation when a trading partner does not regulate emissions. Electricity trade proffers numerous established benefits, including access to cheaper and diversified energy sources (Antweiler 2016), and enables regions supportive of renewables to export green electricity (Yang 2022). However, when engaging in trade, a region cannot control the carbon content of imported electricity. Trade-induced competition may also undermine renewable investment in regions with more stringent environmental policies. Furthermore, renewable intermittency introduces new complexity to policy-making, as weather-dependent trade flows can render static policies inefficient at times. Overlooking intermittency may result in the disregard of some effective policies.

Our modeling approach builds upon the framework of Joskow and Tirole (2000), incorporating renewable intermittency. We consider a two-node network consisting of an exporting region (referred to as the foreign region) with fossil electricity generation, and an importing region (referred to as the home region) endowed with both fossil and renewable generation capabilities, connected by a transmission link. The regulator in the home region is concerned with the climate implications of carbon emissions from the electricity sector and adopts unilateral policies to foster the energy transition.

First, we consider a scenario in which the home region implements carbon pricing (through taxes or emissions permits) and examine how expanding interconnection capacity affects the energy mix in the home region. Next, we introduce a CBAM and renewable subsidies to the policy bundle, analyzing their impact on the energy mix. Finally, we investigate how climate policies alter the incentives to invest in interconnection capacity.

We find that carbon pricing decarbonizes the energy mix through two channels: reducing electricity consumption and increasing the penetration of renewables. However, opening to trade generally raises consumption for most carbon price levels and limits the penetration of renewables. As a result, the home country's carbon footprint of electricity consumption increases under trade. The CBAM removes the cap on renewables by raising the cost of imported power, helping to reduce the trade-induced carbon leakage when only carbon pricing is in place. Nevertheless, to deepen renewable penetration in the foreign market and reverse leakage (i.e., exporting carbon-free power), the CBAM must be complemented by a subsidy on renewables. Regarding interconnection investment, if transmission lines are managed by a Transmission System Operator (TSO), increasing the unilateral carbon price level leads to higher investment in transmission capacity. This expansion in transmission capacity further diminishes the incentives for renewable investment in the home country.

This paper is closely related to two strands of literature. The first concerns the optimal provision of electricity with intermittent renewable energy. A growing body of literature investigates how renewable intermittency impacts the optimal energy mix and market equilibrium in the electricity market. Ambec and Crampes (2012) develop a model characterizing the optimal energy mix between reliable and intermittent sources and analyze the market structure required to decentralize the optimal mix. This literature also explores issues such as how different policy instruments, demand-side responses, and storage technology affect the optimal energy mix in the presence of renewable intermittency (Abrell et al. 2019; Ambec and Crampes 2019; Helm and Mier 2019; Pommeret and Schubert 2022). Yang (2022) extends this framework to consider two regions, analyzing how electricity interconnections influence the optimal energy mix in both regions. They find that even with coordinated carbon policies, electricity interconnection can lead to increased carbon emissions, depending on the energy sources available in the interconnected regions. In contrast, our study examines how unilateral carbon policies affect the energy mix in the regulated region when there is limited capacity for electricity trade.

This paper also contributes to a vast literature on carbon pricing, carbon leakage, and anti-leakage policies. Both theoretical analyses and empirical evidence have demonstrated that unilateral carbon pricing may lead to the relocation of firms due to a loss of competitiveness in the region. Consequently, firms will emit outside the policy jurisdiction, a phenomenon referred to as carbon leakage. To address this leakage issue, the literature discusses several policy instruments, including border carbon adjustment taxes, export rebates, allocation of free emission permits, and emission pricing (Ambec, Pacelli, et al. 2023; 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 contributes to this literature by focusing on the power sector. Electricity differs from other tradable goods in several ways. First, it is a homogeneous good, meaning that electricity produced in any region or from any energy source are perfect substitutes. Second, electricity trade flow is physically constrained by transmission capacity. Therefore, the risk of firms relocating depends on both carbon pricing and available trade capacity. Third, renewable intermittency highlights the weather-dependency of electricity generation from renewable sources. Consequently, 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 how the market structure could affect the effectiveness of incomplete market-based environmental regulations, finding that depending on the industry's competitiveness and the characteristics of regulated firms, incomplete regulation may outperform complete regulation in terms of industry emissions 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 do not consider the impact of renewable intermittency on carbon leakage, or discuss potential policy instruments that could be used to mitigate leakage. A notable exception is Fowlie et al. (2021) which simulates electricity market outcomes under different CBAM designs in the California context. We complement the analyses by characterizing the electricity market outcomes in an analytical framework.

The paper proceeds as follows. Section 2 introduces the model. Section 3 describes the energy mixes under unilateral carbon pricing and analyses how expanding trade impacts the energy mix. Section 4 presents the energy mixes with further climate pricing, namely a CBAM and renewable subsidies. Section 5 discusses how climate policies affect network investment. Through our analysis, the endogenous variables of the energy mixes (capacities, production levels, and prices) are characterized in Propositions, while the economic and policy implications are summarized in the following Corollaries. Section 7 concludes.

2 The model

In the *home country*, electricity can be generated from two sources of energy: fossil fuel f (e.g., coal, gas) and intermittent renewables i (e.g., wind, solar). The "fossil" source is a fully controlled yet polluting technology (e.g., plants burning coal, oil, or natural gas). It has the capacity to produce q_f kWh at a unit operating cost c as long as production does not exceed the installed capacity, K_f. The unit cost of capacity is r_f per kilowatt (kW). It emits air pollutants that cause damage to society. We focus primarily on greenhouse gases, mostly CO_2, although our analysis could encompass other air pollutants such as SO_2, NO_x, or particulate matter. To save on notation, we assume that emissions, denoted E, are measured in kWh of electricity generated from fossil fuel. The carbon price per kWh is denoted by τ.

The second technology relies on a clean yet intermittent primary energy source, such as wind. It enables the production of q_i kWh at zero cost as long as (i) q_i is smaller than the installed capacity K_i, and (ii) the primary energy is available (e.g., wind is blowing). There are two states of nature: "with" and "without" intermittent energy, occurring with frequencies ν and $1-\nu$, respectively. All state-dependent variables are identified by the superscript w and $\overline{w}$ for the two states. We assume $q_i^w = K_i$ and $q_i^{\bar{w}} = 0$.[4] The cost of installing new capacity is r_i per kW. It varies depending on technology and location factors (e.g., weather conditions, proximity to consumers) in the range $[\underline{r}_i, +\infty)$ according to the density function f and the cumulative function F. We assume $\frac{\underline{r}_i}{\nu} > c$, indicating that in the absence of carbon pricing, the average cost of renewables is higher than the marginal cost of thermal power and, therefore, electricity is 100% fossil-fueled.

[4]The assumption of 0 or 1 renewable output is to capture the intermittent nature of renewable resources such as solar or wind. Dispatch renewable sources such as hydro and geothermal are not in the scope of this model.

The total potential capacity that can be installed at cost r_i is $\bar{K}$ for every r_i.[5] We denote by $\tilde{r}_i \geq \underline{r}_i$ the marginal capacity cost of the least efficient generator (e.g., wind turbine or solar panel). Total installed renewable capacity is $K_i = \bar{K}F(\tilde{r}_i)$. We can therefore compute the total cost of installing renewable capacity K_i:

$$C_i(K_i) \equiv \bar{K} \int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i), \tag{1}$$

with $K_i = \bar{K}F(\tilde{r}_i)$ so that $\frac{d\tilde{r}_i}{dK_i} = \frac{1}{\bar{K}f(\tilde{r}_i)}$. The cost function $C_i(\cdot)$ is convex: $C_i'(K_i) = \bar{K}\tilde{r}_i f(\tilde{r}_i)\frac{d\tilde{r}_i}{dK_i} = \tilde{r}_i > 0$, and $C_i''(K_i) = \frac{d\tilde{r}_i}{dK_i} > 0$.

The home country can import electricity from its neighbors. Electricity is imported through high-power lines with a total capacity of K_t kW. We abstract from the energy loss of transmission along the high-power lines. Foreign countries sell electricity at a price of m per kWh (it could be the marginal cost of production under perfect competition). Importers have to pay for using the high-power lines. The tariff is t per kWh transported. The cost of building high-power lines at capacity K_t is denoted $C_t(K_t)$. It is assumed to be increasing and convex: $C_t'(K_t) > 0$ and $C_t''(K_t) > 0$ for every $K_t > 0$. Imported power is fossil-fueled with an emission factor similar to the home country's thermal technology normalized to 1 (1 ton of CO_2 per kWh).

The energy market structure in the home country includes a wholesale market and a retail market. Markets are competitive: firms are price-takers and entry is free. In the retail market, the demand function for electricity is denoted $D(p)$ where p stands for the retail price. The retail price does not vary with the state of nature. By contrast, wholesale electricity prices are weather-dependent: p^w and $p^{\overline{w}}$ denote the price of one kWh of electricity in the wholesale market in states w and $\overline{w}$ respectively. The retail and wholesale electricity prices are related by the zero profit condition for electricity retailers implied by the assumption of free entry in the retail market. Neglecting the operation costs of retailers, the retail price of one kWh of electricity sold to non-reactive consumers is equal to its expected price in the wholesale market $p = \nu p^w + (1-\nu)p^{\overline{w}}$. Throughout this paper, we assume that electricity cannot be stored or curtailed. The only way to balance supply and demand is to rely on production adjustment, transmission and/or price variation. We also assume that $D(0)$ is very high so electricity should be provided under all decarbonization targets we are considering.[6]

The constant price of electricity p implies that demand and, therefore, consumption is the same in both states of nature. Denoting q_j^s the electricity produced from intermittent renewables for $j = i$, fossil energy for $j = f$, or imported for $j = m$, in state s for $s = w, \overline{w}$,

[5] Note that we assume that investing in new intermittent capacity has no effect on the probability of occurrence of state w. The probability only depends on the frequency of windy days (or sunny hours for solar energy). Investing only increases the amount of energy produced in state w.

[6] To make it formal, we assume $D(0) > c + r_f + \tau$ for every carbon price τ.

the market-clearing condition in state w writes $q_i^s + q_f^s + q_m^s = D(p)$ for $s = w, \overline{w}$. Three production levels can be straightforwardly identified. First $q_i^{\overline{w}} = 0$ and $q_i^w = K_i$ under our technological assumption on intermittent renewables. Second, since installing thermal power capacity is costly, the capacity constraint $q_f^s \leq K_f$ for $s = w, \overline{w}$ is binding in one state of nature at least. It is easy to show that it is in state $\overline{w}$ when $K_i > 0$. Suppose the reverse: $q_f^w = K_f > q_f^{\overline{w}}$. It implies that the price in the wholesale market is higher in state w than in state $\overline{w}$, i.e., $p^w > p^{\overline{w}}$. The two market-clearing conditions and $K_i > 0$ imply $q_m^w < q_m^{\overline{w}}$, which can only hold in the opposite case $p^w \leq p^{\overline{w}}$, a contradiction. Hence the market-clearing conditions are:

$$K_i + q_f^w + q_m^w = D(p), \tag{2}$$

$$K_f + q_m^{\overline{w}} = D(p). \tag{3}$$

We first examine the impact of unilateral climate policies on the equilibrium energy mix under exogenous transmission capacity K_t and transportation price t. We assume throughout that $m + t \leq c + r_f$: imported electricity is cheaper without carbon pricing. We limit our discussion to this specific case so that the consideration of carbon leakage due to unilateral carbon pricing is relevant for all carbon prices.[7]

We then investigate the impact of unilateral climate policies on investment in the network capacity and its pricing. In the benchmark case of no carbon price, perfect competition would lead to a transmission price t such that $m + t = c + r_f$ and $t = C_t'(K_t)$ where K_t is the installed capacity. Indeed, the later condition results from the first-order condition of profit maximization for investment into high-power lines given the transportation price t, i.e., maximizing $tK_t - C_t(K_t)$ with respect to K_t. The former condition is an equilibrium condition: transmission capacity increases if $m + t < c + r_f$, and decreases if $m + t > c + r_f$.

3 Energy mix with unilateral carbon pricing

In this section, carbon pricing is the only climate policy. Emissions from thermal power plants are charged τ per kWh, through a carbon tax or in an emission trading scheme. In the latter case, τ is the price of emission allowances. Note that the carbon price τ can be interpreted as the marginal cost of reaching an emission reduction target from a benchmark level. As such τ corresponds to the cost of carbon compatible with this target.

[7] If the home country exports electricity in the absence of a carbon price, i.e., $m > c + r_f + t$, for low carbon price levels $\tau < m - c - r_f - t$, unilateral carbon pricing is sufficient to reduce emissions in the home country. If $m - c - r_f - t < \tau < m + t - c - r_f$, the unilateral carbon pricing reduces electricity export. If $\tau > m + t - c - r_f$, the results from the paper carry over.

We first characterize the energy mix and trade flow depending on the carbon price τ and interconnection capacity K_t in Propositions 1 under the assumption of non-competitive renewables in comparison with imported power as defined below.

Definition 1. *Renewable are non-competitive (compared to imported power) if* $m + t < \frac{\underline{r}_i}{\nu}$.[8] *They are competitive if* $m + t \geq \frac{\underline{r}_i}{\nu}$.

We consider competitive renewables in Appendix A, in which Proposition 6 describes the case of low interconnection capacity while Proposition 7 deals with the reverse case of high interconnection capacity.[9] Each proposition is illustrated with a graph where generation capacities, production, consumption, and electricity trade are plotted depending on the carbon price. We discuss the implications of competitive renewables in section 6.1.

Second, we explain how interconnection impacts the penetration of intermittent renewables and, reversely, how intermittent renewables modify electricity trade. The proofs as well as the definition of all relevant carbon tax thresholds are defined in Appendix B.

3.1 Equilibrium energy mix

Proposition 1. *If* $m+t < \frac{\underline{r}_i}{\nu}$, *the capacities, productions, prices, and emissions are such that:*

(a) no renewables if $\tau < \tau^b$,
$K_i = 0,\ K_f = D(c + r_f + \tau) - K_t = q_f^w,\ q_m^w = q_m^{\overline{w}} = K_t,$
$p^w = c + \tau,\ p^{\overline{w}} = c + \tau + \dfrac{r_f}{1-\nu},\ p = c + r_f + \tau,$
$E = D(p);$

(b) renewables, thermal and imports in state w if $\tau^b \leq \tau \leq \tau^c$,
$K_i = \bar{K}F(\nu(c+\tau)),\ K_f = D(c + r_f + \tau) - K_t,\ q_f^w = K_f - K_i,\ q_m^w = q_m^{\overline{w}} = K_t,$
$p^w = c + \tau,\ p^{\overline{w}} = c + \tau + \dfrac{r_f}{1-\nu},\ p = c + r_f + \tau,$
$E = D(p) - \nu K_i;$

(c) only renewables complemented by K_t *imports in state w if* $\tau^c < \tau < \tau^d$,
$K_i = \bar{K}F(\tilde{r}_i^c)$ *where* $\tilde{r}_i^c$ *is defined by* $\bar{K}F(\tilde{r}_i^c) = D(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f) - K_t,$
$K_f = D(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f) - K_t,\ q_f^w = 0,\ q_m^w = q_m^{\overline{w}} = K_t,$

[8] With a capacity cost $\underline{r}_i$ per kWh for the less costly renewable source of energy and a load factor ν, the levelized cost one kWh generated with renewables is (at least) on average $\frac{\underline{r}_i}{\nu}$. The cost of one kWh of imported power when renewables are producing (in state w) is $m+t$. Renewables are not competitive compared to imported power if $\frac{\underline{r}_i}{\nu} > m + t$.

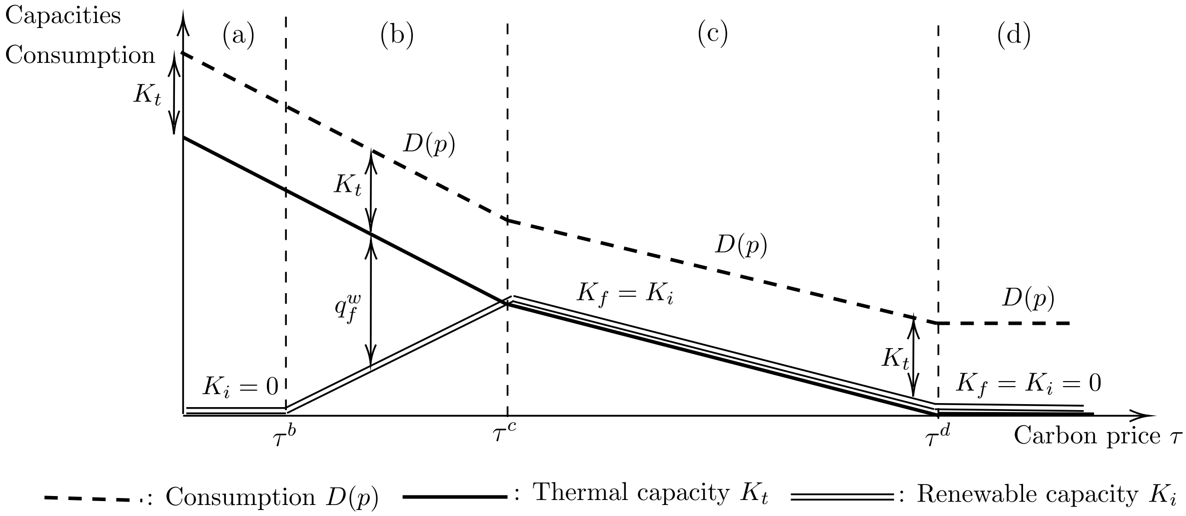
[9] We have decided to include the case of non-competitive renewables in the main text because it is the simplest case. One can then easily see how the CBAM and the subsidies modify the equilibrium outcomes. Moreover, it is when renewables are not competitive that trade and carbon leakage limit most of the decarbonization of electricity generation.

$p^w = \frac{\tilde{r}_i^c}{\nu}$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, $p = \tilde{r}_i^c + (1-\nu)(c+\tau) + r_f$,
$E = (1-\nu)D(p) + \nu K_t$;

(d) *all electricity imported if* $\tau \geq \tau^d$,
$K_i = K_f = q_f^w = 0$, $q_m^w = q_m^{\overline{w}} = K_t$, $p = D^{-1}(K_t)$,
$E = K_t$.

Proposition 1 is illustrated in Figure 1 below.[10]

Figure 1: Energy mix when renewables are not competitive



In case (a) (left part of Figure 1), since $c + \tau < \frac{r_i}{\nu}$ the carbon price is too small to induce investment in renewables. In both states of nature, thermal plants are the only domestic energy providers. They are complemented by imports. For $\tau > 0$, the thermal power long-run cost $c + r_f + \tau$ being higher than the price of imported electricity $m + t$, imports have priority on domestic production in the merit order. The interconnection capacity K_t is fully used to import electricity. The cost of thermal power determines the price of electricity $p = c + r_f + \tau$ so that consumption $D(c + r_f + \tau)$ decreases with the carbon price τ and so do emissions.

For higher values of the carbon price τ, we switch to the case (b) where renewables become competitive in the home country compared to domestic thermal power since now $c + \tau > \frac{r_i}{\nu}$. Investment in renewables is driven by the electricity wholesale price p^w (in state w when renewables are producing), which leads to a cutoff cost denoted by $\tilde{r}_i^b$ for which profits are nil in expectation. The zero profit condition for renewables at cost $\tilde{r}_i^b$ implies that the wholesale price in state w is $p^w = \frac{\tilde{r}_i^b}{\nu}$. Now at this price, since we assume $m + t < \frac{r_i}{\nu}$, importing electricity is profitable and, therefore, K_t kWh are imported in state w. Renewable and imported power are complemented by domestic thermal at cost $c + \tau$.

[10] All the lines in the figures are drawn as straight whereas in some of the cases the functions depicted are not linear.

The wholesale price in state w also equalizes thermal power operating costs $p^w = c + \tau$, which gives the cost of the less profitable renewable $\tilde{r}_i^b = \nu p^w = \nu(c+\tau)$. In state $\overline{w}$, all the thermal power production capacity K_f is used. The wholesale price is such that thermal power producer recoup their capacity cost in state $\overline{w}$, i.e., $p^{\overline{w}} = c+\tau+\dfrac{r_f}{1-\nu}$. Competition among retailers leads to a retailing price of $p = \nu p^w + (1-\nu)p^{\overline{w}} = c + \tau + r_f$ so that electricity consumption $D(p)$ is driven by the social cost of thermal power $p = c+\tau+r_f$. It is decreasing with τ, while investment in renewables $K_i = \bar{K}F(\nu(c+\tau))$ is increasing. As displayed in Figure 1, in case (b), thermal and renewable capacities *substitute* each other when the social cost of carbon increases: K_f decreases and K_i increases with τ. Emissions decrease through two channels: less consumption due to a higher retailing price and substitution of thermal power with renewables in state w.

With an additional increase in τ, renewable capacity matches thermal power capacity: $K_i = K_f$. We move to case (c) where only one source of energy is used domestically in a given state of nature: renewables in state w and thermal power in state $\bar{w}$. Both cover the demand $D(p)$ net of imports K_t so that generation capacities are $K_f = K_i = D(p) - K_t$. Wholesale prices are equal to the marginal cost of the energy source used, that is fossil energy in state $\overline{w}$ with $p^{\overline{w}} = c + r_f + \frac{r_f}{1-\nu}$, and renewable source of energy in state w with $p^w = \dfrac{\tilde{r}_i^c}{\nu}$, where $\tilde{r}_i^c$ is the marginal cost of the less profitable renewable equipment. Retail price is given by the zero profit condition of electricity retailers, that is $p = \nu p^w + (1-\nu)p^{\overline{w}}$, which, given the wholesale prices, leads to a retail price equal to the average production cost of one kWh $p = \tilde{r}_i^c + (1-\nu)(c+\tau) + r_f$. Demand at the retail price yields the threshold cost $\tilde{r}_i^c$ for renewables as a fix point of the market-clearing condition in state w with supply $K_i + K_t$ where $K_i = \bar{K}F(\tilde{r}_i^c)$. In this case, the two sources of energy are no longer substitutes but rather *complements*. Therefore, as fossil energy becomes more expensive, less thermal capacity is installed, which in turn implies less renewable equipment. Electricity consumption has to be reduced, as well as capacity and production from both sources of energy. Emissions are $D(p)$ in state $\overline{w}$ (emissions from thermal power and imports) and K_t in state w (emissions from imports). Total emissions from electricity consumption are $E = (1-\nu)D(p) + \nu K_t$.

When τ increases further, consumption decreases to match connection capacity, i.e., $D(p) = K_t$. We reach case (d) in which all consumption is supplied by imported power. No electricity is generated domestically. Hence no greenhouse gases are emitted from the power sector within the home country territory. Prices are determined by the inverse demand with a supply of electricity constrained by the interconnection capacity K_t. Carbon pricing does not impact any more investment in renewables, electricity generation, and CO_2 emissions because it all happens outside the country.

3.2 Impact of trade on the energy mix

How does electricity trade impact the energy mix? To address this question, it is helpful to use the home country under autarky as a benchmark. In the absence of trade, the carbon price applies to all electricity generated and consumed. The home country maintains full control over the decarbonization of its electricity through carbon pricing. The energy mix under autarky is described by cases (a), (b), or (c) in Proposition 1 with $K_t = 0$ and, thus, $K_f = D(p) = K_i + q_f^w$. The autarky energy mix can be represented in Figure 1 by making the lines K_f (plain line) and $D(p)$ (dashed line) coincide.

We identify two impacts of trade on the energy mix. First, trade limits the penetration of renewables. When renewables are not competitive, renewable generation capacity K_i is bounded by the residual demand net of the interconnection capacity K_t. More renewable sources would have been deployed without trade with a high enough carbon price. The upper bound on renewable penetration is driven by a *substitution effect*: thermal power and renewables are substituted with (cheaper) imported power up to congesting the transmission line. The substitution effect shows up in Figures 1 by introducing a gap between K_f and $D(p)$ of magnitude K_t. Renewable production capacity K_i is reduced for all carbon tax levels higher than τ^c (Proposition 1 and Figure 1). Furthermore, the highest renewable capacity becomes smaller as the volume of trade K_t increases. Differentiating $\hat{K}_i \equiv D(c + r_f + \tau^c) - K_t$ with respect to K_t yields:

$$\frac{d\hat{K}_i}{dK_t} = D'(c + r_f + \tau^c)\frac{d\tau^c}{dK_t} - 1 = \frac{\bar{K}f(\nu(c+\tau^c))}{D'(c + r_f + \tau^c) - \bar{K}f(\nu(c+\tau^c))} < 0. \tag{4}$$

Hence increasing connection capacity K_t reduces the maximal penetration of renewables.

Second, trade modifies electricity consumption through a *scale effect* when the retail price is impacted by (cheaper) imported power. The scale effect shows up for a carbon price higher than τ^c. In contrast, for a low carbon price $\tau < \tau^c$ (cases (a) and (b) of Proposition 1), the retail price is fully determined by the domestic thermal power. Therefore trade does not undermine the reduction of consumption driven by the carbon price. The carbon price is fully passed through the retailing price which incentivizes consumers to cut their power consumption. With a high carbon price ($\tau > \tau^c$), imported power reduces the retail price p by decreasing generation cost in state w. Electricity consumption is higher than without trade, and so are carbon emissions if imported power emits as much as domestic thermal. The carbon price is not as effective in lowering consumption through a higher retailing price than under autarky.

To quantify the scale effect, let us consider case (c) in Propositions 1. Differentiating

$D(p)$ with respect to K_t yields:

$$\begin{aligned}\frac{dD(p)}{dK_t} =& D'(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f)\frac{d\tilde{r}_i^c}{dK_t} \\ =& \frac{D'(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f)}{D'(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f) - \bar{K} f(\tilde{r}_i^c)} > 0\end{aligned} \tag{5}$$

The above relationship shows that expending transmission capacity K_t increases consumption $D(p)$ for a given tax τ.

The two effects of electricity trade on the energy mix, the substitution and the scale effect, increase emission if imported power emits as much as domestic fossil-fueled energy. To see how trade modifies emissions, we differentiate emissions E computed in case (c) in Propositions 1 with respect to interconnection capacity K_t to obtain:

$$\frac{dE}{dK_t} = (1-\nu)D'(p)\frac{dp}{dK_t} + \nu, \tag{6}$$

with $\frac{dp}{dK_t} = \frac{1}{D'(p) - \bar{K} f(p - (1-\nu)(c+\tau) + r_f)} < 0$. The scale effect is captured by the first term of the right-hand side of equation (6). Since $\frac{dp}{dK_t} < 0$ and $D'(p) < 0$, the first right-hand term in (6) is positive meaning that the scale effect increases emissions. The substitution effect in (6) boils down to ν. Each kWh of interconnection capacity added reduces renewable capacity by one kWh, but, since renewables are used with a load factor of ν, the increase of emission is limited to ν kWh on average.[11]

We summarize our analysis of the energy mix in the following Corollary.

Corollary 1. *Electricity trade limits investment in renewables in the country where carbon is priced. It preserves the incentive to reduce electricity consumption driven by the carbon price but increases consumption through a scale effect. Electricity trade increases emissions by substituting away from renewables and reducing retail electricity prices.*

In the next section, we investigate to what extent public policies, such as CBAM and renewable subsidies, could render carbon pricing more effective in decarbonizing the energy mix with interconnection when renewables are non-competitive.

4 Climate policies

4.1 Carbon border adjustment mechanism

We analyze the impact of CBAM on the energy mix. The CBAM is a carbon tariff that charges the carbon price on the carbon content of imported power. Since the emission

[11] Note that only the substitution of renewables by imports matter for emissions, not thermal power because it is as carbon-intensive as imported electricity.

factor of imported power is normalized to one, the carbon tariff is τ per kWh for electricity. We focus again on the case of non-competitive renewables (see Definition 1). We consider the case of imported power cheaper than thermal power $m+t<c$ in Proposition 2, and the opposite case $m+t\geq c$ in Proposition 3. The proofs can be found in Appendix C.

Proposition 2. *If $m+t<\min\{\frac{r_i}{\nu},c\}$, the capacities, productions, prices and emissions with a CBAM are the same as in Proposition 1 when $\tau<\tau^e$ and*

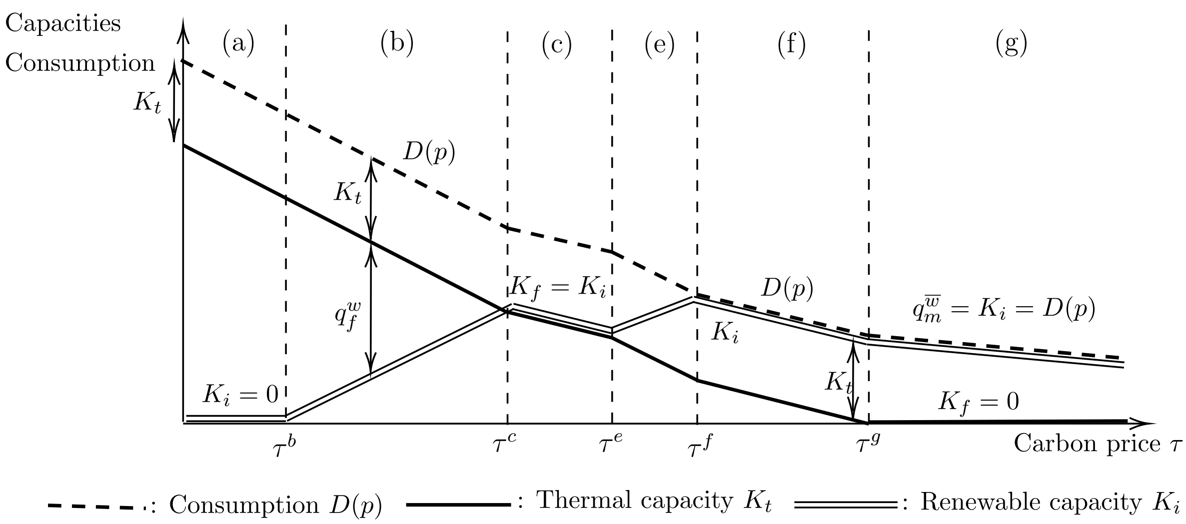
(e) only renewables complemented by imports lower than K_t in state w if $\tau^e<\tau<\tau^f$,
$K_i=\bar{K}F(\nu(m+t+\tau))$, $K_f=D(p)-K_t$, $q_f^w=0$, $q_m^w=D(p)-K_i$, $q_m^{\bar{w}}=K_t$,
$p^w=m+t+\tau$, $p^{\bar{w}}=c+\tau+\frac{r_f}{1-\nu}$, $p=\nu(m+t+\tau)+(1-\nu)(c+\tau)+r_f$,
$E=D(p)-\nu K_i$;

(f) only renewables (no imports) in state w if $\tau^f<\tau\leq\tau^g$,
$K_i=\bar{K}F(\tilde{r}_i^f)$ *where* $\tilde{r}_i^f$ *is defined by* $\bar{K}F(\tilde{r}_i^f)=D(\tilde{r}_i^f+(1-\nu)(c+\tau)+r_f)$,
$K_f=D(\tilde{r}_i^f+(1-\nu)(c+\tau)+r_f)-K_t$, $q_f^w=q_m^w=0$, $q_m^{\overline{w}}=K_t$,
$p^w=\frac{\tilde{r}_i^f}{\nu}$, $p^{\overline{w}}=c+\tau+\frac{r_f}{1-\nu}$, $p=\tilde{r}_i^f+(1-\nu)(c+\tau)+r_f$,
$E=(1-\nu)D(p)$;

(g) only imports lower than K_t in state $\bar{w}$ if $\tau>\tau^g$,
$K_i=\bar{K}F(\tilde{r}_i^g)$ *where* $\tilde{r}_i^g$ *is defined by* $\bar{K}F(\tilde{r}_i^g)=D(\tilde{r}_i^g+(1-\nu)(m+t+\tau))$,
$K_f=q_f^w=q_m^w=0$, $q_m^{\bar{w}}=D(p)<K_t$,
$p^w=\frac{\tilde{r}_i^g}{\nu}$, $p^{\bar{w}}=m+t+\tau$, $p=\tilde{r}_i^g+(1-\nu)(m+t+\tau)$,
$E=(1-\nu)D(p)$.

Figure 2 illustrates the energy mix in Proposition 2.

Figure 2: Equilibrium energy mix with CBAM and non-competitive renewables and thermal power



For a low carbon price $\tau \leq \tau^e$, having the CBAM does not change the energy mix and prices. This is because the marginal source of energy that determines prices is either domestic thermal or renewables, not imports. When the carbon price exceeds τ^e, renewables become competitive compared to imported power thanks to the CBAM. Investment in renewable generation capacity K_i increases with the carbon price τ up to meet demand when the carbon price reaches τ^f. Renewables are pushing away imports. Renewable capacity is no longer capped by imports through interconnection capacity K_t as it was without CBAM. The transmission lines are used only when renewables are not producing in state $\overline{w}$.

When the carbon price exceeds τ^f, electricity becomes carbon-free in state w. We move to case (f) when $\tau^f < \tau \leq \tau^g$. No electricity is imported in state w. The wholesale price in state w is equal to the marginal cost of the least profitable renewable equipment. As before, electricity is generated by a mix of thermal and imports in state $\overline{w}$. When the carbon price exceeds τ^g, the retail electricity price is so high that demand is lower than the interconnection capacity K_t. Hence the transmission line is used below capacity in state $\overline{w}$ and not at all in state w. Electricity consumption further decreases as τ increases since the CBAM makes imported power more expensive.

Now we turn to the case where the thermal power operating cost is lower than the cost of imported electricity. Domestic thermal is dispatched first (if no renewables) followed by imported electricity. This case is described in Proposition 3 below.

Proposition 3. *If $c \leq m + t < \frac{r_i}{\nu}$, the capacities, productions, prices, and emissions with a CBAM are:*

(a1) thermal complemented by imports in state w if $\tau < \tau^{b1}$,
$K_i = 0,\ K_f = q_f^w = D(p) - K_t,\ q_m^w = q_m^{\bar{w}} = K_t,$
$p^w = m + t + \tau,\ p^{\bar{w}} = \dfrac{c + \tau + r_f - \nu(m + t + \tau)}{1 - \nu},\ p = c + \tau + r_f,$
$E = D(p)$;

(b1) thermal complemented by renewables and imports in state w if $\tau^{b1} < \tau < \tau^{c1}$,
$K_i = \bar{K}F(\nu(m + t + \tau)),\ K_f = q_f^w = D(p) - K_t,\ q_m^w = K_t - K_i,\ q_m^{\bar{w}} = K_t,$
$p^w = m + t + \tau,\ p^{\bar{w}} = \dfrac{c + \tau + r_f - \nu(m + t + \tau)}{1 - \nu},\ p = c + \tau + r_f,$
$E = D(p) - \nu K_i$;

(c1) thermal complemented by renewables in state w if $\tau^{c1} < \tau \leq \tau^{e1}$,
$K_i = \bar{K}F(\tilde{r}_i^{c1})$ *where $\tilde{r}_i^{c1}$ is defined by* $\bar{K}F(\tilde{r}_i^{c1}) = K_t,\ K_f = q_f^w = D(p) - K_t,$
$q_m^w = 0,\ q_m^{\bar{w}} = K_t,$
$p^w = \dfrac{\tilde{r}_i^{c1}}{\nu},\ p^{\bar{w}} = \dfrac{c + \tau + r_f - \tilde{r}_i^{c1}}{1 - \nu},\ p = c + \tau + r_f,$
$E = D(p) - \nu K_i$;

(e1) only renewables complemented by thermal in state w if $\tau^{e1} < \tau < \tau^{f1}$,

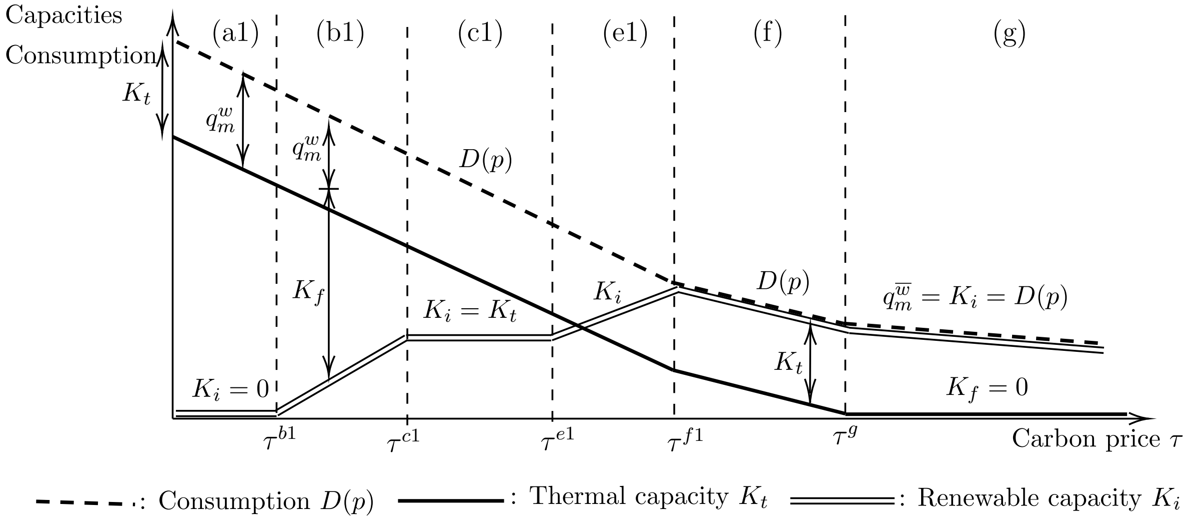
$K_i = \bar{K}F(\nu(c+\tau))$, $K_f = D(p) - K_t$, $q_f^w = D(p) - K_i$, $q_m^w = 0$, $q_m^{\bar{w}} = K_t$,

$p^w = c + \tau$, $p^{\bar{w}} = c + \tau + \frac{r_f}{1-\nu}$, $p = c + \tau + r_f$,

$E = D(p) - \nu K_i$.

When $\tau > \tau^{f1}$, the energy mixes are the same as cases (f) and (g) in Proposition 2.

Figure 3: Equilibrium energy mix with a CBAM with non-competitive renewables and competitive thermal power



When thermal power operating cost is lower than imported power, renewable power substitutes away from imports when $\tau > \tau^{b1}$. Renewable generation capacity increases with the carbon price up to reach interconnection capacity K_t at τ^{c1}. Electricity is imported only in state $\overline{w}$ to save on thermal power production capacity. Thermal power is complemented with renewables in state w and imports in state $\bar{w}$. Renewable capacity does not vary with the carbon price as it is determined by the interconnection capacity: $K_i = K_t$. It is only when the carbon price reaches τ^{e1} that investing further into renewables to substitute imports becomes profitable. Renewable investment K_i further increases. Electricity becomes 100% renewable in state w when $\tau \geq \tau^{f1}$.

By comparing Figure 1 and 3, we can easily see that the CBAM unlocks renewable penetration by replacing imports first and then domestic thermal as the carbon price increases. First imports are replaced by renewables when the carbon price exceeds τ^{b1}. When it reaches τ^{c1}, renewable power becomes competitive compared to imported power thanks to the CBAM. Renewable capacity matches interconnection capacity $K_i = K_t$ and does not vary with the carbon price because renewables are more costly than fossil-fueled energy. The home country is under autarky in state w, and electricity is imported only in state $\overline{w}$. It is only when the carbon price exceeds τ^{e1} that investing in renewables becomes cheaper than running a plant. The wholesale price in state w

reflects thermal power operating costs $c + \tau$ which increases with the carbon price τ. Renewable investment is driven by wholesale market price p^w thus increases with the carbon price τ. For a carbon price exceeding τ^{f1}, demand is fully supplied by renewables in state w so that electricity generation is carbon-free.

The main conclusion of our CBAM analysis is summarized in the Corollary below.

Corollary 2. *A CBAM removes the cap on renewables in the energy mix imposed by interconnection capacity. It does so by increasing the cost of imported power, or by deterring imports. Renewable energy substitutes imported power if its cost is increased, or fossil energy if imports are deterred.*

4.2 Renewable subsidies

We have shown in the previous section that CBAM can reduce electricity imports and can potentially lead to autarky so that electricity becomes 100% renewable when wind or solar power plants are producing. However, CBAM is ineffective in prompting electricity export and, therefore, renewable cannot exceed demand in the home country. Inducing further investment in renewable capacity requires another instrument to make wind or solar power competitive abroad: renewable subsidies. We now investigate how, by subsidizing renewables (capacity or generation), renewable penetration can be improved further with exports. The interconnection line is then used not only to import power but also to export carbon-free electricity.

Let us consider now a subsidy s per kilowatt of renewable production capacity. It reduces the cost of renewable capacity from r_i to $r_i - s$.[12] We examine in this section the effect of such a renewable subsidy on the domestic energy mix.

For renewables to be exported, the subsidy must be such that a kWh generated from renewable equipment and transported through the interconnection line is cheaper than local power in the foreign country. That is, the subsidy allows $\frac{\tilde{r}_i - s}{\nu} + t \leq m$, where $\tilde{r}_i$ is the capacity cost of the least efficient renewable capacity. It is straightforward that renewable export occurs only when there is excess renewable capacity, i.e., $K_i > D(p)$. We characterize the energy mix with a subsidy in Proposition 4 below. The detailed derivation of the results can be found in Appendix C.4.

Proposition 4. *For a given renewable subsidy rate s such that $s > \underline{r}_i - \nu c$, if $m + t < \min\{\frac{\underline{r}_i}{\nu}, c\}$, and a CBAM is implemented, the capacities, productions, prices, and emissions with the subsidy are:*

(b2) thermal power complemented by renewables and imports in state w if $\tau < \tau^{c2}$,
$K_i = \bar{K}F(\nu(c + \tau) + s)$, $K_f = D(p) - K_t$, $q_f^w = D(p) - K_t - K_i$, $q_m^w = q_m^{\overline{w}} = K_t$,

[12] Note that the subsidy on production capacity s per kilowatt is equivalent to a feed-in premium on renewable kWh of s/ν in our model. Renewable subsidy can also be in the form of an export rebate. Here we focus the discussion on subsidizing capacity.

$p^w = c + \tau$, $p^{\overline{w}} = c + \tau + \dfrac{r_f}{1-\nu}$, $p = c + \tau + r_f$,
$E = D(p) - \nu K_i$;

(c2) *only renewables complemented by imports in state w if $\tau^{c2} \leq \tau < \tau^{e2}$,*
$K_i = \bar{K}F(\tilde{r}_i^{c2})$, *where $\tilde{r}_i^{c2}$ is defined by* $\bar{K}F(\tilde{r}_i^{c2}) = D(\tilde{r}_i^{c2} - s + (1-\nu)(c+\tau) + r_f) - K_t$,
$K_f = D(p) - K_t$, $q_f^w = 0$, $q_m^w = q_m^{\overline{w}} = K_t$,
$p^w = \dfrac{\tilde{r}_i^{c2} - s}{\nu}$, $p^{\overline{w}} = c + \tau + \dfrac{r_f}{1-\nu}$, $p = \tilde{r}_i^{c2} - s + (1-\nu)(c+\tau) + r_f$,
$E = (1-\nu)D(p) + \nu K_t$;

(e2) *renewables complemented by imports lower than K_t in state w if $\tau^{e2} \leq \tau < \tau^{f2}$,*
$K_i = \bar{K}F(\nu(m+t+\tau) + s)$, $K_f = D(p) - K_t$, $q_f^w = 0$, $q_m^w = D(p) - K_i$, $q_m^{\overline{w}} = K_t$,
$p^w = m + t + \tau$, $p^{\overline{w}} = c + \tau + \dfrac{r_f}{1-\nu}$, $p = \nu(m+t+\tau) + (1-\nu)(c+\tau) + r_f$,
$E = D(p) - \nu K_i$;

(f2) *only renewables in state w if $\tau^{f2} \leq \tau < \tau^h$,*
$K_i = \bar{K}F(\tilde{r}_i^{f2})$, *where $\tilde{r}_i^{f2}$ is defined by* $\bar{K}F(\tilde{r}_i^{f2}) = D(\tilde{r}_i^{f2} - s + (1-\nu)(c+\tau) + r_f)$,
$K_f = D(p) - K_t$, $q_f^w = 0$, $q_m^w = 0$, $q_m^{\overline{w}} = K_t$,
$p^w = \dfrac{\tilde{r}_i^{f2} - s}{\nu}$, $p^{\bar{w}} = c + \tau + \dfrac{r_f}{1-\nu}$, $p = \tilde{r}_i^{f2} - s + (1-\nu)(c+\tau) + r_f$,
$E = (1-\nu)D(p)$;

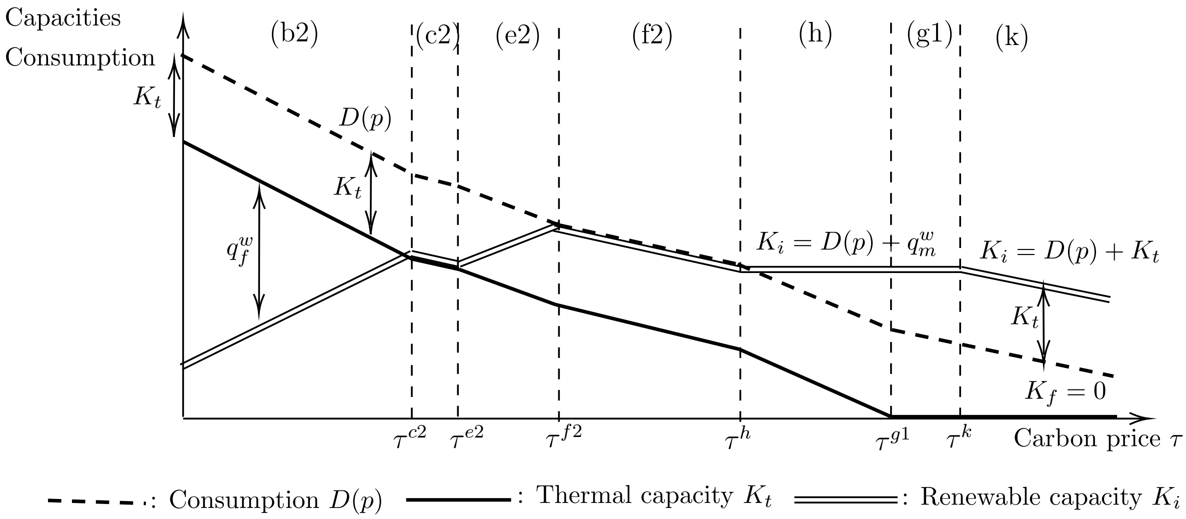
(h) *renewable exports lower than K_t in state w if $\tau^h \leq \tau < \tau^{g1}$,*
$K_i = \bar{K}F(\nu(m-t) + s)$, $K_f = D(p) - K_t$, $q_f^w = 0$, $q_m^w = D(p) - K_i$, $q_m^{\overline{w}} = K_t$,
$p^w = m - t$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, $p = \nu(m-t) + (1-\nu)(c+\tau) + r_f$,
$E = (1-\nu)D(p)$;

(g1) *zero domestic thermal production in both states if $\tau^{g1} \leq \tau \leq \tau^k$,*
$K_i = \bar{K}F(\nu(m-t) + s)$, $K_f = 0$, $q_f^w = 0$, $q_m^w = D(p) - K_i$, $q_m^{\overline{w}} = D(p)$,
$p^w = m - t$, $p^{\overline{w}} = m + t + \tau$, $p = \nu(m-t) + (1-\nu)(m+t+\tau)$,
$E = (1-\nu)D(p)$;

(k) *renewable exports at K_t in state w if $\tau > \tau^k$,*
$K_i = \bar{K}F(\tilde{r}_i^k)$ *where $\tilde{r}_i^k$ is defined by* $\bar{K}F(\tilde{r}_i^k) = D(\tilde{r}_i^k - s + (1-\nu)(m+t+\tau)) + K_t$,
$K_f = 0$, $q_f^w = 0$, $q_m^w = -K_t$, $q_m^{\overline{w}} = D(p)$,
$p^w = \dfrac{\tilde{r}_i^k - s}{\nu}$, $p^{\overline{w}} = m + t + \tau$, $p = \tilde{r}_i^k - s + (1-\nu)(m+t+\tau)$,
$E = (1-\nu)D(p)$.

Proposition 4 is illustrated in Figure 4 below.

Figure 4: Equilibrium energy mix with non-competitive renewables, CBAM, and renewable subsidy



Under the assumption $\frac{r_i - s}{\nu} < m + t < c$, it is profitable to invest in renewables even without any carbon price. For carbon price lower than τ^{c2} (case (b2)), the generation capacity of renewables K_i increases with the carbon price τ up to match with thermal power capacity, i.e., up to $K_i = K_f$. The marginal technology in the merit order being thermal or imports, the subsidy has no effect on wholesale prices. Therefore, the consumption level decreases with the carbon tax, the same as without a subsidy. This is no longer true with higher carbon prices (cases (c2), (e2), (f2)) because renewable energy becomes the marginal technology in state w and, therefore, the subsidy impacts the wholesale price. The energy mix is similar to cases (c), (e), (f) in Proposition 2 except that the subsidy cuts electricity wholesale price in state w as well as the retailing price. Consumption is therefore higher than without subsidy.

When the carbon price exceeds τ^h (cases (h), (g1), and (k)), renewable power is cheaper than foreign electricity when exported to the foreign country. Renewable production capacity K_i is set such that the cutoff renewable cost equals the foreign market price when exported (including the transport fee t): $\frac{\tilde{r}_i - s}{\nu} + t = m$. The wholesale price in state w is determined by revenue from exporting power $p^w = m - t$ (the price of electricity abroad m net of the interconnection fee t). Electricity becomes more expensive as the carbon price increases in case (h) and, therefore, domestic consumption decreases. On the other hand, the wholesale price in state w is unchanged at $p^w = m - t$ and so is renewable production capacity K_i. More renewable generation is exported and less is consumed domestically in state w.

At the carbon price τ^{g1}, consumption is so low that thermal power is no longer needed. All electricity is supplied by imports K_t in state $\overline{w}$ and by renewables in state w. Consumption decreases further as the carbon price increases above τ^{g1}. More renewables are exported up to the interconnection capacity K_t with carbon price τ^k. A further increase in the carbon price reduces renewable penetration K_i because it lowers consumption while the extra renewable generation cannot be exported due to limited interconnection capacity.[13]

The above result shows that a renewable subsidy can potentially reduce the carbon footprint of foreign electricity consumption through renewable power exports. This cannot be achieved with a carbon price or CBAM. Other forms of subsidy would lead to the same outcomes of exporting renewables and thus unlocking renewable investment. First, instead of subsidizing s per kW of capacity, a feed-in premium of νs kWh on top of the wholesale price would lead to the same energy mix. Second, a subsidy on exported renewable power (a feed-in premium applied only to exported power) could do the job. The subsidy σ must fill the gap between the wholesale prices in state w in the home country and the foreign country net of the network tariff. It must be such that $p^w = m - t + \sigma$, hence $\sigma = p^w - m + t$.

We summarize the main message of the subsidy analysis below.

Corollary 3. *The CBAM must be complemented by a subsidy on renewables to increase renewable generation above domestic consumption in state w. The interconnection line is then used to export power rather than importing power in state w. Low-carbon electricity is exported, which makes electricity consumption abroad less carbon-intensive. A further increase in the carbon price does not modify investment in renewables while it reduces consumption in the home country. Renewable capacity decreases with the carbon price when exports are limited by interconnection capacity.*

5 Interconnection

We now investigate the role of interconnection in decarbonizing the energy mix in the home country. First, we examine the impact of the transmission price t and discuss how adjusting t can further enhance the penetration of renewables. Subsequently, under the assumption that access to interconnection capacity is auctioned off with transmission rights, we analyze how these rights affect the investment in interconnection capacity K_t.

5.1 Transmission pricing

Consider first the case of unilateral carbon price without any other climate policy described in Section 3. For a given carbon price τ, a higher transmission price t increases the cost of imported power $m + t$. Doing so makes renewables competitive compared to imported power if $t > \frac{r_i}{\nu} - m$.[14] Renewables capacity $K_i = K_t$ is installed for low carbon

[13]If the subsidy is in the form of a export rebate, the effect of subsidies on domestic consumption is removed. Therefore the subsidy does not change the energy mix until the carbon tax is higher than τ^h.

[14]To be precise, increasing transmission right from t to t' with $m + t < \frac{r_i}{\nu}$ and $m + t' > \frac{r_i}{\nu}$ modifies the energy mix from the one described in Proposition 1 to one in Proposition 6 or in Proposition 7.

tax levels. Electricity generation becomes 100% renewable in state w with $K_i = D(p)$ for high carbon price with low interconnection capacity.[15]

It is worth noting that domestic thermal capacity and production are not impacted by the transmission price in most energy mixes in Proposition 1 to 4. Under our assumption $m + t \leq c + r_f$, imported power is cheaper than thermal power. The latter being the marginal energy source in the merit order, its cost determines the wholesale price in state $\overline{w}$ (and not the cost of imported power $m + t$). The only way that the transmission charge impacts thermal power capacity K_f is indirectly through the wholesale price in state w. In some energy mixes such as case (e) in Proposition 2 and (h) in Proposition 4, imported power is the marginal energy source in state w and $p^w = m + t + \tau$ and $p^w = m - t$, respectively. The transmission price is passed through final consumers in the retail price p. Thermal power capacity is therefore impacted by the transmission charge only indirectly through the retailing market.

5.2 Investment in interconnection with transmission rights

When the TSO is remunerated with transmission rights instead of a constant transportation price, $t = 0$ in the energy mixes described above. Transmission rights are auctioned off: producers and retailers bid for the use of the interconnection power line. They are willing to bid up to the price difference between domestic and imported power in the wholesale market, that is $p^s - m$ (or $p^s - (m + \tau)$ with the CBAM) in state $s = w, \overline{w}$. Following Joskow and Tirole (2000), the price paid for transmission rights is the nodal price difference which corresponds to the congestion rent (if any). All congestion rent goes to the TSO which invests its revenue into interconnection infrastructure. The TSO earns an expected profit of[16]

$$E[\Pi] = \nu(p^w - m)q_m^w + (1 - \nu)(p^{\overline{w}} - m)q_m^{\overline{w}} - C_t(K_t) \tag{7}$$

without the CBAM, or

$$E[\Pi] = \nu(p^w - m - \tau)q_m^w + (1 - \nu)(p^{\overline{w}} - m - \tau)q_m^{\overline{w}} - C_t(K_t) \tag{8}$$

with the CBAM.

As shown in the energy mixes derived in Proposition 1 to 4, $p^s - m$ (or $p^s - (m + \tau)$ with the CBAM) is strictly positive when the power line is congested, in which case $q_m^s = K_t$. When the line is not congested, there is zero congestion rent as $p^s = m$ (or $p^s - (m + \tau)$ with the CBAM).

[15] The higher transmission price switches the energy mix from the one graphed in Figure 1 to the one in Figure A.1 or in Figure A.2 depending on transmission capacity.

[16] Note that the same expected profit is achieved if the TSO does the trading itself. It would thus earn $p^s - m$ in state $s = w, \overline{w}$ per kW of interconnection capacity.

We distinguish between three cases. First case, the interconnection lines are congested in both states of nature w and $\overline{w}$. This corresponds to all cases in Proposition 1, (a), (b), and (c) in Proposition 2, (a1) in Proposition 3, and (b2) and (c2) in Proposition 4. Since $p = \nu p^w + (1-\nu)p^{\overline{w}}$ and $q^w = q^{\overline{w}} = K_t$, the expected profit in (7) and (13) can be written as:

$$E[\Pi] = (p - m)K_t - C_t(K_t), \tag{9}$$

or if with the CBAM

$$E[\Pi] = (p - m - \tau)K_t - C_t(K_t). \tag{10}$$

Differentiating (9) and (10) with respect to K_t and assuming $p > m + \tau$, we obtain the following first-order condition that determines investment in transmission capacity K_t maximizing the expected profit:[17]

$$p - m = C_t'(K_t) \tag{11}$$

and

$$p - m - \tau = C_t'(K_t), \tag{12}$$

respectively. Investment in interconnection is driven by the gap between the retail price and the cost of imported power. Interconnection capacity is thus $K_t = C_t'^{-1}(p - m)$ (or $K_t = C_t'^{-1}(p-m-\tau)$ with CBAM) when renewables are not competitive (see Definition 1), where p is defined in Propositions 1, 2, and 3 depending on the energy mixes. Therefore, with only carbon pricing, the incentive to invest in interconnection capacity increases with a higher carbon price since there is higher transmission rent. However, CBAM deters the incentive to invest in interconnection as carbon price increases since the price gap does not depend on τ in cases (a) and (b) in Proposition 2 and is decreasing in τ in case (c).

Second case, the interconnection lines are congested only when renewables are not producing that is only in state $\overline{w}$. It turns out to be the case for (e) and (f) in Proposition 2, (b1), (c1), (e1), and (f) in Proposition 3, and (e2), (f2), and (h) in Proposition 4. Since $p^w = m + \tau$ with $t = 0$ or $q_m^w = 0$, and $q_m^{\overline{w}} = K_t$, the expected profit in (7) becomes:

$$E[\Pi] = (1 - \nu)(p^{\overline{w}} - m - \tau)K_t - C_t(K_t) \tag{13}$$

Differentiating (13) with respect to K_t yields:

$$(1 - \nu)(p^{\overline{w}} - m - \tau) = C_t'(K_t). \tag{14}$$

Investment in interconnection is determined by the gap between the wholesale mar-

[17] The assumption $p > m$ implies that the interconnection capacity is binding.

ket price and the cost of imported power during the congestion periods as well as the frequency of congestion $1-\nu$. The interconnection capacity that maximizes the TSO's expected profit is thus $K_t = C_t'^{-1}\left((1-\nu)(p^{\overline{w}} - m - \tau)\right)$, where the wholesale price $p^{\overline{w}}$ depends on the energy mixes in Propositions 2 to 4. Interestingly, in all but case (c1) of Proposition 3, the investment in interconnection does not depend on the carbon price. In case (c1), the investment in interconnection increases with a higher carbon price.

Third case, the interconnection lines are congested in the opposite direction only when renewables are producing to export power. This is only the case of energy mix (k) in Proposition 4. Expected profit is $E[\pi] = \nu(m - p^w)K_t - C_t(K_t)$ with $p^w = \dfrac{\tilde{r}_i^k - s}{\nu}$.[18] Investment in interconnection is determined by the first-order condition $\nu m - \tilde{r}_i^k + s = C_t'(K_t)$. It is increasing with the renewable subsidy s as well as the carbon price τ (through $\tilde{r}_i^k$): interconnection capacity expands with more stringent climate policies.

Comparing the above first-order conditions on interconnection capacity, we show in Appendix D the following result.

Proposition 5. *With only carbon pricing, investment in interconnection is increasing with the carbon price τ. The CBAM deters the incentive to investment interconnection from increased carbon pricing, except in case (c1). The renewable subsidy and carbon pricing increase interconnection investment when renewables are exported at full transmission capacity.*

We have established that electricity trade reduces the effectiveness of the carbon price in decarbonizing the energy mix. Proposition 5 highlights that the effectiveness is further reduced with the incentives to invest in interconnection capacity. As the carbon price increases, investing in interconnection becomes more profitable so that transmission capacity is expanded. More interconnection means more electricity imported which reduces further the carbon price effectiveness.

The CBAM lowers the transmission rent by fully pricing the carbon content of imported electricity. It effectively hinders leakage by removing the rent-seeking motivation to invest in interconnection when the carbon price increases. The only exception is in case (c1) of Proposition 2, where higher carbon prices lead to higher interconnection investment, but at a lower rate compared to without the CBAM.

Subsidies make renewables competitive compared to imported power which reduces the profitability of interconnection investment. It thus leads to less interconnection capacity in the long run, which increases the effectiveness of carbon pricing. A further increase in renewable subsidies allows the use of interconnection lines to export renewables. Wind and solar power substitute thermal power generation abroad. The carbon leakage problem is thus reversed. Carbon emissions do not leak abroad with carbon-intensive imports.

[18] Note that in case (k) of Proposition 4, electricity consumption $D(p)$ is lower than the transmission capacity K_t. The transmission line is used below capacity for imports in state $\bar{w}$.

Instead, the carbon content of electricity consumption abroad is reduced thanks to the exports of low-carbon wind and solar power by means of the interconnection line.

We summarize the main messages of this section below.

Corollary 4. *The transmission price plays a similar role as CBAM to enhance the effectiveness of carbon pricing with trade. A higher carbon price increases investment in interconnection which further increases carbon leakage. This effect can be mitigated by implementing a CBAM or subsidizing renewables which reduces the profitability of interconnection investment. However, when renewable generation is exported up to the interconnection capacity, a higher subsidy increases the profitability of interconnection and, thus, the incentives to expand interconnection capacity.*

6 Discussion

Before ending the paper with concluding comments, we briefly investigate how our results would change with alternative assumptions on the technologies. We consider first the case of competitive renewables. Next, we improve the availability of renewable energy sources across states of nature. Last we allow for energy storage and demand response.

6.1 The case of competitive renewables

In Appendix A, we explain how having competitive renewables modifies the energy mix then there is only carbon price. We separately consider two cases: low transmission capacity (Proposition 6) and high transmission capacity (Proposition 7). We summarize the key takeaways. First, competitive renewables result in a higher share of renewables in the energy mix for all carbon prices compared to non-competitive renewables. This can be visualized by comparing Figure 1 with Figure A.1 or A.2. With competitive renewables, some renewable capacity is installed at zero or low carbon prices. Windmills and solar farms push imported power out of the market when producing. For higher carbon prices, renewable capacity is no longer decreasing with the carbon price as it replaces imported power. The interconnection line is used at capacity only in state $\overline{w}$ when renewables are not producing.

Second, competitive renewables dampen the limiting effect of trade on renewables penetration. Renewable generation capacity K_i is not bounded by the residual demand as in the case of non-competitive renewables. Competitive renewables can substitute some all or some imported power depending on the carbon price and the transmission capacity. The cost of imported power still renders the more expensive renewable sources unprofitable, which would have been profitable without trade with a high enough carbon price. Trade not only push out domestic thermal power, but also lead to renewable adoption as low carbon prices compare to autarky. That is, if renewables are competitive, trade has a positive effect on renewable adoption.

Third, when renewables are competitive, renewable investment K_i increases with the transmission price in some cases. This happens when imported power is the marginal energy source in the merit order that makes the wholesale price in state w. Hence $p^w = m + t$ and renewable investment $K_i = \bar{K}F(\nu(m+t))$ is increasing with t.

Lastly, competitive renewables reduce the incentive to invest in interconnection capacity. With competitive renewables, transmission lines are congested only when renewables are not producing that is only in state $\overline{w}$.[19] The TSO thus operates with the expected profit

$$E[\Pi] = (1-\nu)(p^{\overline{w}} - m)K_t - C_t(K_t). \tag{15}$$

The interconnection capacity that maximizes the TSO's expected profit is thus $K_t = C_t'^{-1}\left((1-\nu)(p^{\overline{w}} - m)\right)$, where the wholesale price $p^{\overline{w}}$ depends on the energy mix in Propositions 6 and 7. Comparing (9) and (15), we can show that the incentive to invest in interconnection capacity at any given carbon price τ is strictly lower under competitive renewables than under non-competitive renewables.

6.2 More reliable renewables

Following our previous work (Ambec and Crampes 2019; Yang 2022), we have modeled intermittent electricity generation for wind and solar power with two states of nature: one with full production and the other with none. This simplification makes renewable intermittency more salient and provides a tractable model to obtain explicit solutions. However, it fails to encompass the improved availability of renewable energy sources with higher production capacity. As different renewable energy sources (e.g., solar PV, solar thermal power, onshore and offshore wind, tidal power) are exploited in different locations, one can expect that the low power generation events from renewables become scarcer, and of lower magnitude. It means that in our model, the frequency $1-\nu$ of state $\overline{w}$ decreases and some renewable energy is produced during this unfavorable event. The latter feature can be captured in our model by assuming that a share α of the overall renewable production capacity is generated in state $\overline{w}$ with $0 \leq \alpha < 1$.[20] We investigate how a minimum renewable availability α modifies the energy mix. We summarize the main changes based on our mathematical computation available in Appendix E.

The reliability of renewable relaxes the market-clearing condition (3) in state $\overline{w}$ by allowing for αK_i kWh of renewable generation to meet demand. The renewables produced in state $\overline{w}$ also generate revenue for the renewable producers, thus modifying the zero-

[19] It turns out to be the case in most energy mixes when renewables are competitive (in energy mixes $(a2)$, $(b3)$, (l), (f), (g) in Propositions 6 and in $(a3)$, (m) in Proposition 7).

[20] We thank an anonymous referee for suggesting this extension of our model.

profit condition of the least profitable renewable unit. Consequently, it has four impacts on the energy mix when there is only a carbon price (Proposition 1). First, it reduces the threshold carbon prices τ^b (for which investing in renewables is profitable), and τ^c (for which renewable capacity matches domestic demand net of import). Second, it increases investment in renewables K_i for a given carbon price in case (b) and (c) of Proposition 1. Third, it also increases consumption in case (c) as the retail price decreases in α. This is because the revenue stream in state $\overline{w}$ for the renewable producers reduces the wholesale price in w governed by the zero-profit condition. Fourth, reliable renewables modify the link between production capacities from $K_i = K_f$ to $K_f = (1-\alpha)K_i$ in case (c), although renewables and thermal are still complements.

With CBAM (Proposition 2), increased reliability of renewables α has similar impacts on the energy mix. First, it changes the threshold carbon prices: it reduces τ^k (for which renewable substitutes imported electricity) and τ^f (for which when renewables fully satisfy demand in state w). Second, it increases renewable capacity for a given carbon price in cases (b)-(g) in Proposition 2. Third, when renewables are the marginal generation technology (cases (c), (f), and (g)), reliable renewables also reduce the retail price and increase consumption.

When renewable subsidy comes into play, renewable reliability α lowers the subsidy rate needed to export power. Importantly, in case (k) of Proposition 4, there could also be exports in state $\overline{w}$ if α is sufficiently large, which further reduces emissions abroad.

Overall, increased reliability of renewables, as captured by the parameter α, does not change qualitatively our results. It does have on impact on the energy mix by increasing investment in renewables, and reducing reliance on thermal power and imported power for a given carbon price. Carbon emissions are thus lower. Nevertheless, carbon leakage remains an issue. It can be addressed by a CBAM and renewables subsidies in a similar way than when renewables are not producing in state $\overline{w}$ with $\alpha = 0$.

6.3 Energy storage and demand response

Throughout the paper, we did not consider technological or behavioral solutions to deal with intermittency that are energy storage and demand response. Such solutions can easily be added to the model, and the equilibrium energy could (less easily) be derived in another one-page proposition. To save this further analysis, we can take advantage of previous studies with the same model and get some insights.

Technically, both energy storage and demand response relax the market-clearing conditions (2) and (3) by allowing the transfer of supply (with storage) or demand (with demand response) from the state of nature w to the state of nature $\overline{w}$. Electricity is stored when the wind turbines are spinning and used when they are not. As for demand response, consumers equipped with smart meters and reacting to wholesale prices are buying more electricity at price p^w (when it is cheaper) and less at price $p^{\overline{w}}$. Consequently, with either energy storage or demand response, renewables capacity K_i is no longer tied with the capacity of back energy sources that are thermal power K_f or imported power K_t. As shown in Ambec and Crampes (2019), thermal power phases out when energy storage phases in, whereas renewable capacity increases to feed the high-scale batteries installed (see Figure 1 in Ambec and Crampes 2019). Similarly, as shown in Ambec and Crampes (2021), a higher share of "reactive" consumers with dynamic prices decreases thermal power capacity and carbon emissions. More renewables are installed to feed demand when price are low, that is when the wind is blowing. Hence, by untying K_i with K_f and K_t, both energy storage and dynamic prices help to uncap renewable penetration. Both solutions also tend to reduce carbon emissions by lowering fossil-fueled energy. Public policy that fosters investment in energy storage equipment (e.g. pumped-storage hydropower or batteries) and the adoption of dynamic prices with smart meters are extending renewable generation capacity and reducing carbon emissions.

7 Conclusion

Our analysis demonstrates that trade diminishes the effectiveness of carbon pricing in decarbonizing the energy mix. Importing carbon-intensive power through interconnection lines constrains renewable investments. This effect is exacerbated by the increased profitability of interconnection investment at higher carbon prices, which results in greater interconnection and, consequently, reduced renewable generation for the same carbon price. A CBAM enhances renewable investment for a sufficiently high carbon price. However, it is insufficient to make the carbon price fully effective when renewables are not competitive. To address this, CBAM should be complemented with renewable subsidies, enabling the export of carbon-free electricity and, thus, reversing carbon leakage. Consequently, the investment in interconnection driven by carbon pricing can be leveraged to further decarbonize electricity consumption abroad.

We conclude with the following remarks. First, throughout the paper, we assume that the foreign electricity price is fixed. The underlying assumptions are that (i) foreign countries do not respond by altering their climate policies and (ii) the trade volume does not modify the merit order in the foreign market. These assumptions can be relaxed to investigate how energy mixes abroad change in response to the home country's climate policy. However, this would require endogenizing the climate and trade policies of all trading partners within a game theory framework. We leave this aspect for future research.

Second, although we emphasize that trade reduces the effectiveness of carbon pricing, it is not our intention to advocate for limiting electricity interconnection. Electricity interconnection can lead to a more competitive market, enabling consumers to access cheaper electricity by utilizing lower-cost energy sources from neighboring countries. Moreover, electricity interconnection enhances power system resiliency by allowing countries to rely on each other for energy supply during times of shortage or emergencies. Interconnection also facilitates the integration of renewable energy sources across larger geographical areas, enabling the sharing of resources, balancing of intermittency, and optimizing the use of renewable energy (MacDonald et al. 2016; Yang 2022). Therefore, investing in interconnection is vital for energy security and efficiency. However, as interconnection modifies the energy mix of interconnected countries, it is essential to consider appropriate policy responses to ensure we reap the benefits of interconnection without exacerbating climate change.

Lastly, the policy instruments we analyze in this paper (carbon pricing, CBAM, transmission prices and rights, and renewable subsidies) should be carefully coordinated, as they impact the energy mix, interconnection, and trade differently. Many countries and regions now price carbon emissions (through taxation or emissions trading schemes) to combat climate change.[21] However, carbon prices vary across countries. Trading with a region that has a lower or no carbon price results in carbon leakage. A CBAM mitigates carbon leakage by leveling the playing field domestically. Higher transmission prices serve a similar purpose. However, both CBAM and higher transmission prices do not level the playing field abroad. To reverse carbon leakage through exporting carbon-free power, CBAM needs to be complemented by renewable subsidies. Subsidizing renewables for export may be welfare-enhancing, given that carbon emissions abroad impact the climate as much as domestic ones. For some level of carbon prices (e.g., case (k) in Proposition 4), a renewable subsidy has the following effects, namely increasing consumer gross surplus through lowered retail prices, increasing total capacity cost for renewables and thermal power, reducing the variable cost of electricity generation by exporting renewables, and reducing emissions abroad. The combination of the above effects may lead to increased domestic social welfare. In this paper, we have identified the role of each climate policy. However, determining the optimal combination of climate policies on a case-by-case basis, depending on the country's objectives, remains an open question.

[21] See the World Bank Carbon Pricing Dashboard (https://carbonpricingdashboard.worldbank.org) for the up-to-date country/regional level carbon policy adoption.

A Energy mix with competitive renewables

A.1 Competitive renewables with low transmission capacity

Proposition 6. *If $m + t \geq \frac{r_i}{\nu}$ and $K_t < \bar{K}F(\nu(m+t))$, the capacities, productions, prices, and emissions are the same as cases (b) and (c) in Proposition 1 if $\tau^{b2} \leq \tau \leq \tau^{b3}$ and $\tau^c < \tau \leq \tau^l$, and:*

(a2) only renewables and thermal under full capacity (no import) in state w if $\tau < \tau^{b2}$,
$K_i = \bar{K}F(\tilde{r}_i^{a2}) = q_f^w$ *where* $\tilde{r}_i^{a2}$ *is defined by* $\bar{K}F(\tilde{r}_i^{a2}) = K_t$,
$K_f = D(c + r_f + \tau) - K_t = q_f^w$, $q_m^w = 0$, $q_m^{\overline{w}} = K_t$,
$p^w = \frac{\tilde{r}_i^{a2}}{\nu}$, $p^{\overline{w}} = \frac{c + r_f + \tau - \tilde{r}_i^{a2}}{1-\nu}$, $p = c + r_f + \tau$,
$E = D(p) - \nu K_t$;

(b3) only renewables and thermal below capacity (no import) in state w if $\tau^{b2} \leq \tau \leq \tau^{b3}$,
$K_i = \bar{K}F(\nu(c+\tau))$, $K_f = D(c + r_f + \tau) - K_t, q_f^w = D(c + r_f + \tau) - K_i$, $q_m^w = 0$, $q_m^{\overline{w}} = K_t$,
$p^w = c + \tau$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, $p = c + r_f + \tau$,
$E = D(p) - \nu K_i$;

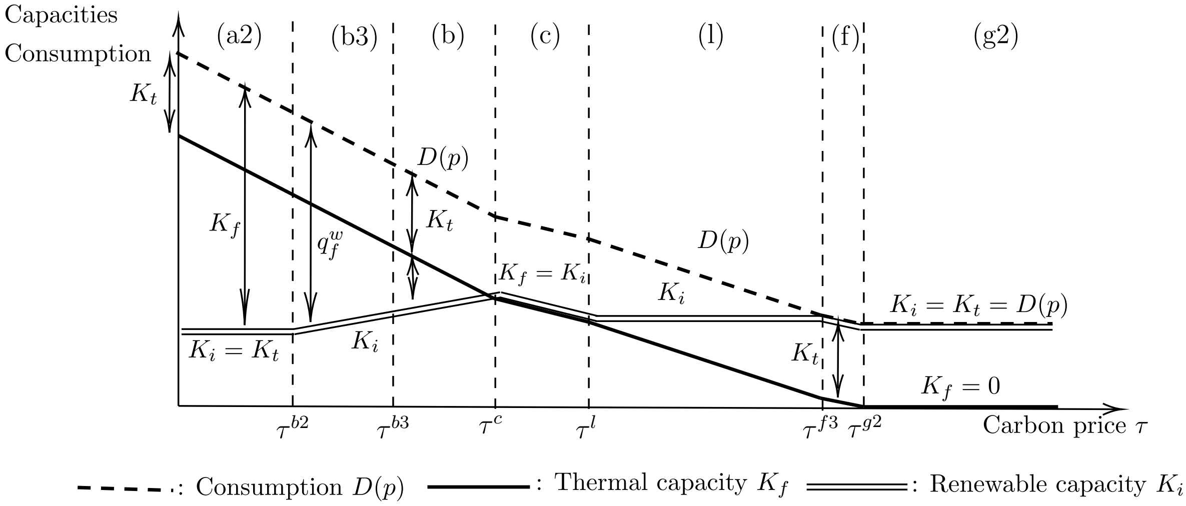
(l) only renewables complemented by less than K_t imports in state w if $\tau^l < \tau \leq \tau^{f3}$,
$K_i = \bar{K}F(\nu(m+t))$, $K_f = D(\nu(m+t) + (1-\nu)(c+\tau) + r_f) - K_t$, $q_f^w = 0$,
$q_m^w = D(\nu(m+t) + (1-\nu)(c+\tau) + r_f) - \bar{K}F(\nu(m+t))$, $q_m^{\overline{w}} = K_t$,
$p^w = m + t$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, $p = \nu(m+t) + (1-\nu)(c+\tau) + r_f$,
$E = D(p) - \nu K_i$;

(f) only renewables (no imports) in state w if $\tau^{f3} < \tau \leq \tau^{g2}$,
$K_i = \bar{K}F(\tilde{r}_i^f)$ *where* $\tilde{r}_i^f$ *is defined by* $\bar{K}F(\tilde{r}_i^f) = D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f)$,
$K_f = D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f) - K_t$, $q_f^w = q_m^w = 0$, $q_m^{\overline{w}} = K_t$
$p^w = \frac{\tilde{r}_i^f}{\nu}$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, $p = \tilde{r}_i^f + (1-\nu)(c+\tau) + r_f$,
$E = (1-\nu)D(p)$;

(g2) only imports in state $\overline{w}$ and only renewables in state w if $\tau > \tau^g$,
$K_i = \bar{K}F(\tilde{r}_i^g)$ *where* $\tilde{r}_i^g$ *is defined by* $\bar{K}F(\tilde{r}_i^g) = K_t$, $K_f = q_f^w = 0$, $q_m^w = 0$, $q_m^{\overline{w}} = K_t$
$p^w = \frac{\tilde{r}_i^g}{\nu}$, $p^{\overline{w}} = \frac{D^{-1}(K_t) - \tilde{r}_i^g}{1-\nu}$, $p = D^{-1}(K_t)$,
$E = (1-\nu)K_t$.

Proposition 6 is illustrated in Figure A.1 below.

Figure A.1: Energy mix when renewables are competitive and transmission capacity is low



In contrast to Proposition 1, when renewables are less costly than imported power, they push imported power out of the market when producing, i.e., in state w. With low interconnection capacity K_t as assumed here, renewable capacity matches interconnection capacity $K_i = K_t$ for very low carbon prices (case (a2)). Renewables in state w and imports in state $\overline{w}$ are complemented with thermal power plants producing at their maximal capacity K_f in both states of nature. The wholesale price in state w is determined by the price of the more costly renewable capacity $p^w = \frac{\tilde{r}_i^{a2}}{\nu}$, where the total renewable capacity equals the interconnection capacity K_t. Thermal power complements imports in state $\bar{w}$ to meet the market clearing condition. Since the thermal producers are making positive profits in state w because $p^w > c+\tau$, the free entry and zero-profit condition will lead to the thermal producer charging a lower price in state $\overline{w}$ that recovers the capacity cost. That is, the wholesale price in state $\bar{w}$ is $p^{\overline{w}} = \dfrac{c + \tau + r_f - \tilde{r}_i^{a2}}{1-\nu}$, lower than the long term marginal cost of thermal power $c + \tau + \frac{r_f}{1-\nu}$. Retail competition leads to $p = c + \tau + r_f$. It increases with the carbon tax and, therefore, consumption decreases with τ.[22] In case (b3), the carbon price drives further investment into renewables that exceeds interconnection capacity $K_i > K_t$, and, therefore, thermal power plants are producing below capacity in state w. Since $\tilde{r}_i^{b3} = \nu(c + \tau)$, renewable capacity K_i increases with the carbon price which leads to a further reduction in carbon emissions.

For middle-range carbon prices ($\tau^{b3} < \tau \leq \tau^l$), the energy mix is similar to cases (b) and (c) of Proposition 1 (with non-competitive renewables). What is new compared to Proposition 1 is that K_i stops decreasing with τ when $\tau > \tau^l$. The energy mix is described in case (l). The interconnection power lines are used below capacity since less than K_t kWh are imported when renewables are producing in state w. The wholesale price in

[22] Note that since renewable capacity does not change with τ when $\tau < \tau^{b2}$, the share of renewables in the energy mix increases with τ.

state w is determined by the price of imported electricity $p^w = m + t$. At this price, the assumption of competitive renewables $m+t \geq \frac{r_i}{\nu}$ implies that investing in renewable is profitable up to a capacity $K_i = \bar{K}F(\nu(m+t))$. Renewables are complemented with imported electricity. Thermal power is used only in state $\overline{w}$. The wholesale price in state $\overline{w}$ covers the long-term marginal cost of fossil-fueled electricity. Fossil energy is complemented with imports using the full capacity of the interconnection line K_t. The retail price p increases with τ and, therefore, consumption decreases with τ. Yet investment in renewables K_i does not change with τ since it is driven by $p^w = m + t$ (the cost of imported power).

For a higher carbon price $\tau > \tau^{f3}$, renewable production capacity K_i is enough to supply demand. We move to case (f) when $\tau^{f3} < \tau \leq \tau^{g2}$. No electricity is imported in state w. The wholesale price in state w is equal to the marginal cost of the least profitable renewable equipment. As before, electricity is generated by a mix of thermal and imports in state $\overline{w}$. If $\tau > \tau^{g2}$, consumption is low enough so that it can be supplied with imports in state $\overline{w}$ and with renewables in state w. No fossil-fueled energy is produced domestically. Electricity generation in the home country is carbon free but consumption is not. A further increase in the carbon price is ineffective on consumption-based emissions because all fossil energy is burnt out of the borders.

We now move to the case of interconnection capacity higher than renewable capacity $K_t > \bar{K}F(\nu(m+t))$, still with competitive renewables.

A.2 Competitive renewables with high transmission capacity

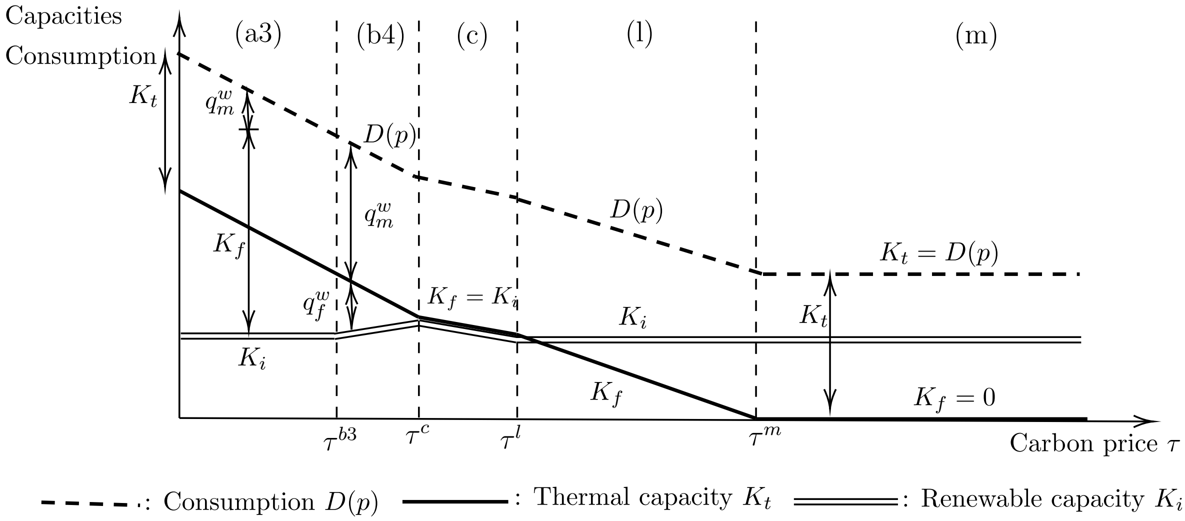
Proposition 7. *If $m+t \geq \frac{r_i}{\nu}$ and $K_t > \bar{K}F(\nu(m+t))$, the capacities, productions, prices and emissions are defined as in Proposition 6 cases (b), (c) and (l) for $\tau^{b3} \leq \tau \leq \tau^l$, and*

(a3) renewables, fossil energy and imports in state w if $\tau < \tau^{b3}$,
$K_i = \bar{K}F(\nu(m+t))$, $K_f = D(c + r_f + \tau) - K_t = q_f^w$, $q_m^w = K_t - K_i$, $q_m^{\overline{w}} = K_t$,
$p^w = m + t$, $p^{\overline{w}} = \dfrac{c + r_f + \tau - \nu(m+t)}{1-\nu}$, $p = c + r_f + \tau$,
$E = D(p) - \nu K_i$;

(m) only imports in state $\overline{w}$ and renewables complemented by imports in state w if $\tau > \tau^m$
$K_i = \bar{K}F(\nu(m+t))$, $K_f = q_f^w = 0$, $q_m^w = K_t - \bar{K}F(\nu(m+t))$, $q_m^{\overline{w}} = K_t$,
$p^w = m + t$, $p^{\overline{w}} = \dfrac{D^{-1}(K_t) - \nu(m+t)}{1-\nu}$, $p = D^{-1}(K_t)$,
$E = K_t - \nu K_i$.

Proposition 7 is illustrated in Figure A.2 below.

Figure A.2: Energy mix when renewables are competitive and transmission capacity is high



Compared to Proposition 6, extending interconnection capacity K_t above $\bar{K}F(\nu(m+t))$ modifies the energy mix for extreme values of the carbon price τ. Renewable investment K_i is no longer limited by the transmission capacity K_t but rather by the cost of imported electricity $m+t$. First, it happens for very low carbon price $\tau < \tau^{b3}$. The energy mix switches from case (a2) of Proposition 6 to case (a3) of Proposition 7. In state w, both thermal and renewables run at full capacity, and the transmission lines are used below capacity to import electricity that clears the market. The wholesale electricity price in state w is determined by the marginal electricity source, which is imported electricity in this case, thus $p^w = m+t$. In both states, thermal capacity is used fully. The zero-profit condition of thermal producers yield the wholesale price $p^{\bar{w}} = \dfrac{c+\tau+r_f-\nu(m+t)}{1-\nu} < c+\tau+\dfrac{r_f}{1-\nu}$, since they make a positive profit in state w. The retail price is $p = c + r_f + \tau$ which increases with carbon price. With higher transmission, renewable capacity is higher and leads to a reduction of the overall emissions from domestic electricity consumption. Although demand decreases with the carbon tax, renewable capacity is not affected when $\tau < m+t-c$.

Second, for very high carbon price $\tau > \tau^m$, the energy mix is case (m) of Proposition 7. Transmission capacity K_t does not bound upward renewable investment K_i as in cases (f) and (g2) of Proposition 6. Renewable investment is driven by the cost of imported power $m+t$, and thus $K_i = \bar{K}F(\nu(m+t))$. Renewables are complemented by imported power in state w, while only imported power (no domestic thermal) is supplied in state $\bar{w}$. Demand is determined by K_t and the retail price is $p = D^{-1}(K_t)$. The wholesale price in state w is given by the zero-profit condition of the more costly renewable capacity and thus $p^w = m+t$. The wholesale price in state $\bar{w}$ is pinned down by the zero profit of retailers. The carbon price has no impact on demand or renewable capacity since there are zero territorial emissions.

B Proof of Propositions 1, 6, and 7

B.1 Supply and equilibrium conditions

- Thermal producers earn $\pi_f = \nu\left(p^w - c - \tau\right) q_f^w + (1-\nu)\left(p^{\overline{w}} - c - \tau\right) K_f - r_f K_f$ with $q_f^w \leq K_f$ where q_f^w denotes the thermal generation in state w:

  (i) Whenever $p^w > c + \tau$, thermal producers supply $q_f^w = K_f$ and they earn $\pi_f = \left[\nu p^w + (1-\nu)p^{\overline{w}} - (c + \tau + r_f)\right] K_f$. Then $K_f > 0$ whenever $\nu p^w + (1-\nu)p^{\overline{w}} \geq c + \tau + r_f$, $K_f = 0$ otherwise.

  (ii) Whenever $p^w < c+\tau$, they produce $q_f^w = 0$ and earn $\pi_f = \left[(1-\nu)\left(p^{\overline{w}} - c - \tau\right) - r_f\right] K_f$. Then if $p^{\overline{w}} \geq c + \tau + \frac{r_f}{1-\nu}$ they fix $K_f > 0$; otherwise $K_f = 0$.

  (iii) Whenever $p^w = c + \tau$ they produce any value $q_f^w \in [0, K_f]$, $K_f > 0$ if $p^{\overline{w}} \geq c + \tau + \frac{r_f}{1-\nu}$ and $K_f = 0$ otherwise.

  The competitive thermal producers must also satisfy the zero-profit condition.

- Renewable producers earn $\pi_i = \nu p^w \bar{K} F(r_i) - \bar{K} \int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i)$ whenever $\tilde{r}_i \geq \underline{r}_i$. Renewable production plants at lower costs r_i are installed up to the threshold cost $\tilde{r}_i$. Free entry implies that $\tilde{r}_i$ is defined by the expected zero profit condition per kilowatt hour $\nu p^w - \tilde{r}_i = 0$ if $\nu p^w > \underline{r}_i$. Otherwise, $K_i = 0$.

- Wholesale market prices depends on the marginal generation technology in the two states.

- Retailers earn $\pi_r = \left(p - \nu p^w - (1-\nu)p^{\overline{w}}\right) q$. They operate as long as $p \geq \nu p^w + (1-\nu)p^{\overline{w}}$. Free entry zero profit per kilowatt hour sold: $p = \nu p^w + (1-\nu)p^{\overline{w}}$.

- If $p^s > m + t$, K_t kWh are imported in state $s = w, \overline{w}$. If $m - t < p^s < m + t$, electricity is neither exported nor imported in state s. If $p^s < m - t$ electricity is exported in state s. If $p^s = m - t$, electricity can be exported but the transmission capacity is not binding.

- The two market-clearing conditions (2) and (3) hold.

B.2 The carbon price thresholds

The thresholds on the carbon price τ^i for $i = b, b2, b3, c, d, f3, g2, l, m$ are defined by the following relationships:

In proposition 1,

$$\tau^b: \qquad \tau^b = \frac{r_i}{\nu} - c, \tag{B.1}$$

$$\tau^c: \qquad \bar{K}F(\nu(c+\tau^c)) + K_t = D(c + r_f + \tau^c), \tag{B.2}$$

$$\tau^d: \qquad K_t = D(\tilde{r}_i^c + (1-\nu)(c+\tau^d) + r_f). \tag{B.3}$$

In proposition 6,

$$\tau^{b2}: \qquad \bar{K}F(\nu(c+\tau^{b1})) = K_t, \tag{B.4}$$

$$\tau^{b3}: \qquad \tau^{b2} = m + t - c, \tag{B.5}$$

$$\tau^l: \qquad \bar{K}F(\nu(m+t)) + K_t = D(\nu(m+t) + (1-\nu)(c+\tau^l) + r_f), \tag{B.6}$$

$$\tau^{f3}: \qquad \bar{K}F(\nu(m+t)) = D(\nu(m+t) + (1-\nu)(c+\tau^{f3}) + r_f), \tag{B.7}$$

$$\tau^{g2}: \qquad \tau^{g2} = \frac{D^{-1}(K_t) - F^{-1}\left(\frac{K_t}{\bar{K}}\right) - r_f}{1-\nu} - c. \tag{B.8}$$

In proposition 7,

$$\tau^m: \qquad K_t = D(\nu(m+t) + (1-\nu)(c+\tau^m) + r_f). \tag{B.9}$$

B.3 Proof of Proposition 1

Case (a): When $\tau < \frac{r_i}{\nu} - c$, renewables are not profitable so that $K_i = 0$. Thermal power are running in both states of nature under full capacity. This outcome is compatible with the zero-profit and free-entry conditions for prices $p^w = c+\tau$, $p^{\overline{w}} = c+\tau+\frac{r_f}{1-\nu}$, and $p = c + r_f + \tau$. Indeed, $p^w < \frac{r_i}{\nu}$ keeps renewables out of the market. Thermal plants produce at full capacity in state w but they earn a zero operating profit. This is why $p^{\overline{w}}$ must be high enough to reimburse the fixed cost during period $\overline{w}$. Given those wholesale prices, the zero-profit condition of electricity retailers yields $p = \nu p^w + (1-\nu)p^{\overline{w}} = c + r_f + \tau$. Thermal power capacity is determined by demand at this price $K_f = D(c + \tau + r_f)$. Finally, emissions are K_f in the home country and K_t abroad. Since emissions from abroad are the same as domestic fossil power, emissions from electricity consumption in home country are $E = K_f + K_t = D(p)$.

Case (b): Prices are the same as in case (a). But now, since $\tau > \frac{r_i}{\nu} - c$ by (B.1), we have $p^w > \frac{r_i}{\nu}$ so that investment in renewable becomes profitable. The installed capacity is such $K_i = \bar{K}F(\tilde{r}_i^b)$ with $\tilde{r}_i^b = \nu p^w = \nu\,(c+\tau)$ so that profits are nil on the more costly renewable equipment, i.e., those with cost $\tilde{r}_i^b$ per kilowatt (equipment at costs $r_i < \tilde{r}_i^b$ generate strictly positive profits). Furthermore, under the assumption $m + t < \frac{r_i}{\nu}$, since $\frac{r_i}{\nu} \leq \tilde{r}_i^b$, we have $m+t < p^w$ and, therefore, $q_m^w = K_t$. With the retail price $p = c+\tau+r_f$, consumption is $D(c+\tau+r_f)$. The market-clearing condition in state w determines thermal power production $q_f^w = D(c+\tau+r_f) - K_i - K_t = D(c+\tau+r_f) - \bar{K}F(\nu(c+\tau)) - K_t$, where the last equality is due to the above characterization of K_i. In state $\overline{w}$, investment into thermal power fills the gap between between consumption and imports, i.e., $K_f = D(p) - K_t = D(c+\tau+r_f) - K_t$. With wholesale prices p^w and $p^{\overline{w}}$, thermal power producers earn zero profit. The tax rate τ^c is such that renewables production and imports meet residual demand at those price, hence (B.2). Emissions are $K_f + K_t$ in state $\bar{w}$ and $q_f^w + K_t$ in state w. Using $K_f + K_t = D(p)$ and $q_f^w = D(p) - (K_i + K_t)$, we obtain $E = D(p) - \nu K_i$.

Case (c): When $\tau^c < \tau < \tau^d$, $D(p) < K_i + K_t$ with the prices of case (b), so that thermal power is not longer needed in state w. Hence $q_f^w = 0$: electricity is supplied by imports and renewables in state w. Since $\frac{r_i}{\nu} > m+t$, renewable energy is more expensive than imported power and, therefore, the wholesale price in state w is determined by the zero-profit condition for the renewable farms with highest costs $\tilde{r}_i^c$ that is $p^w = \frac{\tilde{r}_i^c}{\nu}$. Hence total capacity for renewables is $K_i = \bar{K}F(\tilde{r}_i^c)$. Thermal power plants are running only in state $\overline{w}$ because $c + \tau > p^w$. Their zero-profit condition per kWh writes: $(1-\nu)p^{\overline{w}} = (1-\nu)(c+\tau)+r_f$, which yields $p^{\overline{w}} = c+\tau+\frac{r_f}{1-\nu}$. Given the above wholesale prices p^w and $p^{\overline{w}}$, the zero-profit condition for retailers leads to a retail price of $p = \nu p^w + (1-\nu)p^{\overline{w}} = \tilde{r}_i^c + (1-\nu)(c+\tau) + r_f$. Electricity consumption is $D(p) = D(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f)$. With the above values of K_i and p, the market-clearing condition is state w yields:

$$\bar{K}F(\tilde{r}_i^c) + K_t = D(\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f). \tag{B.10}$$

The threshold renewable cost $\tilde{r}_i^c$ is a fix point of (B.10), the left-hand side being increasing with $\tilde{r}_i^c$ while the right-hand side is decreasing with $\tilde{r}_i^c$. Differentiating (B.10) with respect to τ yields $\frac{d\tilde{r}_i^c}{d\tau} = \frac{D'(p)}{\bar{K}f(\tilde{r}_i^c) - D'(p)} < 0$ where the last inequality holds because D is decreasing in p. Hence $\tilde{r}_i^c$ is decreasing in τ, and so is renewable capacity $K_i = \bar{K}F(\tilde{r}_i^c)$. It becomes nil for $\tau > \tau^d$ where τ^d is the tax rate such that import matches consumption, i.e., defined by $K_t = D(\tilde{r}_i^c + (1-\nu)(c+\tau^d) + r_f)$. Emissions are from $K_f + K_t = D(p)$ kWh of thermal power and K_t kWh of imported power in state $\overline{w}$. It yields $E = D(p) + \nu K_t$.

Case (d): When $\tau > \tau^d$, the demand can be supplied by imports in both states of nature, hence, $K_i = K_f = 0$. Wholesale prices should satisfy $m + t \leq p^w < \frac{r_i}{\nu}$ and $m + t \leq p^{\overline{w}} < c + \tau + \frac{r_f}{1-\nu}$ to deter investment in both renewable and thermal power but cover the cost of importing electricity. Supply equals demand in the retailing market $K_t = D(p)$ leads to the retail price $p = D^{-1}(K_t)$. All emissions K_t are abroad with $E = K_t$.

B.4 Proof of Proposition 6

Case (a2): When renewables are competitive, that is $m + t > \frac{r_i}{\nu} > c$, then when $0 < \tau < \tau^{b2}$, where τ^{b2} is defined by $\bar{K}F(\nu(c+\tau^{b2})) = K_t$, imported power in state w is more costly than both renewables and domestic thermal power. We have $c+\tau < \frac{\tilde{r}_i^{a2}}{\nu} < m+t$ if $K_t < \bar{K}F(\nu(m+t))$, where $\tilde{r}_i^{a2}$ is defined by $\bar{K}F(\tilde{r}_i^{a2}) = K_t$. So in state w, thermal power runs at full capacity $q_f^w = K_f = D(p) - K_t$, and renewables satisfy the residual demand, so $K_i = \bar{K}F(\tilde{r}_i^{a2}) = K_t$. There is no import in state w, $q_m^w = 0$. We have $p^w = \frac{\tilde{r}_i^{a2}}{\nu} < m+t$ so the more costly renewable equipment get zero profit. Since $p^w > c + \tau$, the thermal producers makes positive profit in state w. In state $\overline{w}$, imported power is cheaper than domestic thermal, with the average cost $c + \tau + \frac{r_f}{1-\nu}$, so electricity is imported up to transmission capacity $q_m^{\overline{w}} = K_t$. Since the thermal producers make positive profit in state w, the zero-profit condition will lead to a lower-than-average-cost-price in state $\bar{w}$, that is $p^{\overline{w}} = \frac{c + r_f + \tau - \tilde{r}_i^{a2}}{1-\nu}$. So the retail price is $p = \nu p^w + (1-\nu)p^{\overline{w}} = c + r_f + \tau$. Finally, emissions are $D(p)$ in state w and $D(p) - K_i$ in state $\overline{w}$, which yields $E = D(p) - \nu K_i$.

Case (b3): If $\tau^{b2} \leq \tau \leq \tau^{b3}$, where $\tau^{b3} = m + t - c$, then it is profitable to invest in renewable capacity that exceeds K_t. In state w, imported electricity is still more expensive than domestic power. The average cost of renewables is equal to the marginal cost of thermal power so $\tilde{r}_i^{b3} = c + \tau < m + t$. The demand is met by renewables and thermal power $D(p) = K_i + q_f^w$, with $K_i = \bar{K}F(\nu(c+\tau))$. There is no imported electricity in state w $q_m^w = 0$. So the wholesale price is $p^w = c + \tau$. Thermal power runs at full capacity in state $\overline{w}$ and is equal to demand net of import $K_f = D(p) - K_t$. The wholesale price is $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$ to recover the capacity cost of thermal, and the retail price $p = c + \tau + r_f$. Emissions are $\nu q_f^w + (1-\nu)K_f$ in the home country and $(1-\nu)K_t$ abroad. Emissions from electricity consumption are $E = D(p) - \nu K_i$.

Case (b): If $\tau^{b3} < \tau \leq \tau^c$, where τ^c is defined in (B.2), then we are back to the same situation as case (b) in Proposition 1.

Case (c): If $\tau^c < \tau \leq \tau^l$, where τ^l is defined in (B.6), then we are back to the same situation as case (c) in Proposition 1.

Case (l): If $\frac{r_i}{\nu} < m + t$, then there exists a value τ^l such that $\tilde{r}_i^c$ defined in (B.10) satisfies $\frac{\tilde{r}_i^c}{\nu} = m+t$. In this case, the zero-profit condition for renewable producers implies $p^w = \frac{\tilde{r}_i^c}{\nu} = m+t$ and $K_i = \bar{K}F(\nu(m+t))$. Furthermore, since thermal power plants are not running in state w because $p^w < c+\tau$, the zero-profit conditions for thermal producers and retailers yield the respective prices $p^{\overline{w}} = c+\tau+\frac{r_f}{1-\nu}$ and $p = \nu(m+t)+(1-\nu)(c+\tau)+r_f$ respectively. Consumption is thus $D(p) = D(\nu(m + t) + (1 - \nu)(c + \tau) + r_f)$. The market-clearing condition in state w this level of consumption and renewable production $K_i = \bar{K}F(\nu(m + t))$ defines τ^l in (B.6). Thermal power capacity K_f is given by the market-clearing condition in state $\overline{w}$:

$$K_f + K_t = D(\nu(m+t) + (1-\nu)(c+\tau) + r_f). \tag{B.11}$$

Imports in state w q_m^w are giving by the market-clearing condition in state w with $K_i = \bar{K}F(\nu(m+t))$:

$$q_m^w + \bar{K}F(\nu(m+t)) = D(\nu(m+t) + (1-\nu)(c+\tau) + r_f). \tag{B.12}$$

Emissions are $K_f + K_t = D(p)$ in state $\overline{w}$ and $q_m^w = D(p) - K_i$ in state w, which yields $E = D(p) - \nu K_i$. The threshold tax rates τ^f is defined such that $q_m^w = 0$ in (B.12).

Case (f): When $\tau^f < \tau < \tau^{g2}$ and $K_t < \bar{K}F(\nu(m+t))$, no electricity is imported in state w and demand is fully satisfied by renewables. The capacity of renewables is given by the market clearing condition $K_i = \bar{K}F(\tilde{r}_i^f)$ where $\tilde{r}_i^f$ needs to be defined. The zero profit condition for the more costly renewable production equipment yields $p^w = \frac{\tilde{r}_i^f}{\nu}$. As long as $\tau < \tau^{g2}$, fossil energy is used in the home country in state $\overline{w}$ and therefore, by the thermal power producers' zero-profit condition, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$. The threshold τ^{g2} is such that $K_f = 0$ and the renewable capacity defined above is equal to the transmission capacity K_t. The zero-profit condition for retailers yields a retailing price yields $p = \tilde{r}_i^f + (1-\nu)(c+\tau) + r_f$. Since $q_m^w = 0$, the market-clearing condition in state w writes $\bar{K}F(\tilde{r}_i^f) = D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f)$ which defines $\tilde{r}_i^f$. Thermal power production capacity is given by the market-clearing condition in state $\overline{w}$, which yields $K_f = D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f) - K_t$. It is strictly positive as long as $\tau < \tau^{g2}$, where τ^{g2} is such that $K_f = 0$ and $D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f) = K_t$ which gives (C.3). Emissions are $K_f + K_t = D(p)$ in state $\bar{w}$, no emission in state $\overline{w}$ K_t which yields $E = (1-\nu)D(p)$.

Case (g2): When $\tau > \tau^{g2}$ and $K_t < \bar{K}F(\nu(m+t))$, imports equals to consumption K_t in state $\bar{w}$ so that domestic fossil energy is not used, i.e., $q_m^{\overline{w}} = K_t$ and $K_f = 0$. Renewable generation matches consumption K_t, i.e., $K_i = K_t$, which, since $K_i = \bar{K}F(\tilde{r}_i^g)$, defines the threshold type $\tilde{r}_i^g$ by $\bar{K}F(\tilde{r}_i^g) = K_t$. Hence $q_m^w = 0$. The zero-profit condition of the less profitable windmill with cost $\tilde{r}_i^g$ determines the wholesale price $p^w = \frac{\tilde{r}_i^g}{\nu}$. Retail price is given by the retail market-clearing condition $D(p) = K_t$, which leads to $p = D^{-1}(K_t)$. The zero-profit condition on the retailing market determines the wholesale price in state $\overline{w}$: $p^{\overline{w}} = \frac{D^{-1}(K_t) - \tilde{r}_i^g}{1-\nu}$. Emissions are K_t from abroad only in state $\overline{w}$, hence $E = (1-\nu)K_t$.

B.5 Proof of Proposition 7

Case (a3): When renewables are competitive and $0 < \tau < \tau^{b3}$, it is profitable to invest in renewables up $\frac{\tilde{r}_i^{a3}}{\nu} = m + t > c + \tau$ if $K_t \geq \bar{K}F(\nu(m+t))$. Imported electricity is

the marginal technology that determines the wholesale price in state w $p^w = m + t$. So domestic demand is met by thermal power, renewables, and imported electricity. The transmission lines are used under capacity and q_m^w is given by the market clearing condition $K_f + K_i + q_m^w = D(p)$, where $K_f = D(p) - K_t$, $K_i = \bar{K}F(\nu(m+t))$. In state $\overline{w}$ domestic thermal complements imported electricity, and the zero-profit condition gives $p^{\overline{w}} = \dfrac{c + r_f + \tau - \nu(m+t)}{1-\nu}$. The expected retail price is thus $p = c + r_f + \tau$. Therefore, the market clearing condition gives $K_f + K_t = D(c + r_f + \tau)$ and $q_m^w = K_t - K_i$. Emissions are $D(p)$ in state w and $D(p) - K_i$ in state $\overline{w}$, which yields $E = D(p) - \nu K_i$.
Case (m): When $\tau > \tau^m$ and $K_t > \bar{K}F(\nu(m+t))$, all electricity is imported in state $\overline{w}$. The threshold τ^m is defined such that $K_f = 0$ in (B.11). Consumption is thus $K_t = D(p)$ and therefore the retail price is $p = D^{-1}(K_t)$. Production from renewables $K_i = \bar{K}F(\nu(m+t))$ in state w is complemented by imported power $q_m^w = D^{-1}(K_t) - \bar{K}F(\nu(m+t))$. The wholesale price in state w is given by the zero-profit condition of renewable producers $p^w = m + t$. The wholesale market price in state $\overline{w}$ is given by the zero-profit condition of retailers $p^{\overline{w}} = \dfrac{D^{-1}(K_t) - \nu(m+t)}{1-\nu}$. Emissions are K_t in state w and $K_t - K_i$ in state $\overline{w}$, which yields $E = K_t - \nu K_i$.

C Proofs of Propositions 2, 3, and 4

C.1 The carbon price thresholds

The thresholds on the carbon price τ^i for $i = b1, c1, c2, e, e1, e2, f, f1, f2, g, h, k$ are defined by the following relationships:

In proposition 2,

$$\tau^e: \qquad \bar{K}F(\nu(m+t+\tau^e)) + K_t = D(\nu(m+t+\tau^e) + (1-\nu)(c+\tau^e) + r_f) \tag{C.1}$$

$$\tau^f: \qquad \bar{K}F(\nu(m+t+\tau^f)) = D(\nu(m+t+\tau^f) + (1-\nu)(c+\tau^f) + r_f) \tag{C.2}$$

$$\tau^g: \qquad \tau^g = \frac{D^{-1}(K_t) - F^{-1}\left(\dfrac{K_t}{\bar{K}}\right) - r_f}{1-\nu} - c. \tag{C.3}$$

In proposition 3,

$$\tau^{b1}: \qquad \tau^{b1} = \frac{r_i}{\nu} - m - t \tag{C.4}$$

$$\tau^{c1}: \qquad \bar{K}F(\nu(m+t+\tau^{c1})) = K_t \tag{C.5}$$

$$\tau^{e1}: \qquad \bar{K}F(\nu(c+\tau^{e1})) = K_t \tag{C.6}$$

$$\tau^{f1}: \qquad \bar{K}F(\nu(c+\tau^{f1})) = D(c+\tau^{f1}+r_f) \tag{C.7}$$

In proposition 4,

$$\begin{aligned}
\tau^{c2}: &\quad \bar{K}F(\nu(c+\tau^{c2})+s) = D(c+\tau^{c2}+r_f) - K_t && \text{(C.8)}\\
\tau^{e2}: &\quad \bar{K}F(\nu(m+t+\tau^{e2})+s) = \\
&\quad D(\nu(m+t+\tau^{e2})+(1-\nu)(c+\tau^{e2})+r_f) - K_t && \text{(C.9)}\\
\tau^{f2}: &\quad \bar{K}F(\nu(m+t+\tau^{f2})+s) = \\
&\quad D(\nu(m+t+\tau^{f2})+(1-\nu)(c+\tau^{f2})+r_f) && \text{(C.10)}\\
\tau^{l}: &\quad \bar{K}F(\nu(m-t)+s) = D(\nu(m-t)+(1-\nu)(c+\tau^{l})+r_f) && \text{(C.11)}\\
\tau^{g1}: &\quad D(\nu(m-t)+(1-\nu)(m+t+\tau^{g1})) = K_t && \text{(C.12)}\\
\tau^{k}: &\quad \bar{K}F(\nu(m-t)+s) = D(\nu(m-t)+(1-\nu)(m+t+\tau^{k})) + K_t && \text{(C.13)}
\end{aligned}$$

C.2 Proof of Proposition 2

When $\tau \leq \tau^e$, τ^e as defined in (C.1), CBAM does not change equilibrium prices and thus the energy mix. We are in cases (a), (b) or (c) from Proposition 1.

Case (e): When $\tau^e < \tau < \tau^f$, τ^f defined in (C.2), renewables become competitive compared to imported electricity with a carbon tariff. It is profitable to invest in renewables up to $\frac{\tilde{r}_i^e}{\nu} = m + t > c$. Domestic demand is met by renewables and imported power thus the wholesale price in state w is $p^w = m + t + \tau$. The transmission lines are under under capacity and q_m^w is given by $K_i + q_m^w = D(p)$. In state $\bar{w}$ domestic thermal complements imported electricity and the zero-profit condition gives $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$. The expected retail price is $p = \nu(m+t+\tau) + (1-\nu)(c+\tau) + r_f$. Emissions are $q_m^w = D(p) - K_i$ in state w and $K_f + K_t = D(p)$ in state $\overline{w}$. Emissions from electricity consumption in home country are thus $E = D(p) - \nu K_i$.

Case (f): When $\tau^f < \tau < \tau^g$, τ^g defined in (C.3), no electricity is imported in state w and demand is fully satisfied by renewables. The capacity of renewables is given by the market clearing condition $K_i = \bar{K}F(\tilde{r}_i^f)$ where $\tilde{r}_i^f$ needs to be defined. The zero profit condition for the more costly renewable production equipment yields $p^w = \frac{\tilde{r}_i^f}{\nu}$. As long as $\tau < \tau^g$, fossil energy is used in the home country in state $\overline{w}$ and therefore, by the thermal power producers' zero-profit condition, $p^{\overline{w}} = c + \tau + \dfrac{r_f}{1-\nu}$. The threshold τ^g is such that $K_f = 0$ and the renewable capacity defined above is equal to the transmission capacity K_t. The zero-profit condition for retailers yields a retailing price yields $p = \tilde{r}_i^f + (1-\nu)(c+\tau) + r_f$. Since $q_m^w = 0$, the market-clearing condition in state w writes $\bar{K}F(\tilde{r}_i^f) = D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f)$ which defines $\tilde{r}_i^f$. Thermal power production capacity is given by the market-clearing condition in state $\overline{w}$, which yields $K_f = D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f) - K_t$. It is strictly positive as long as $\tau < \tau^g$, where τ^g is such that $K_f = 0$ and $D(\tilde{r}_i^f + (1-\nu)(c+\tau) + r_f) = K_t$ which gives (C.3). Emissions are $K_f + K_t = D(p)$ in state $\bar{w}$, no emission in state $\overline{w}$ K_t which yields $E = (1-\nu)D(p)$.

Case (g): When $\tau > \tau^g$, imported power is sufficient to meet demand in state $\bar{w}$. Domestic demand is met by renewables only in state w and by imports in state $\overline{w}$. Wholesale price are thus $p^w = \frac{\tilde{r}_i}{\nu}$ and $p^{\overline{w}} = m + t + \tau$. Retail price is $p = \nu p^w + (1-\nu)p^{\overline{w}} = \tilde{r}_i + (1-\nu)(m+t+\tau)$. The cutoff renewable cost denoted $\tilde{r}_i^{g1}$ is given by the market clearing condition is state w: $K_i = \bar{K}F(\tilde{r}_i^{g1}) = D(\tilde{r}_i^{g1} + (1-\nu)(m+t+\tau))$. As carbon price increases, domestic demand decreases. Emissions are 0 in state w and $D(p)$ in state $\overline{w}$, hence $E = (1-\nu)D(p)$.

C.3 Proof of Proposition 3

When $m + t > c$, domestic thermal power is cheaper than imported electricity in state w if used just under capacity K_f. Since $m+t < c+r_f$ by assumption, K_f is still determined by $K_f = \max\{D(p) - K_t, 0\}$. In state $\bar{w}$, $q_m^{\overline{w}} = K_t$ for all levels of carbon price. We can focus the analysis on what happens in state w. Depending on the carbon price, we have the following cases:

Case (a1): When $\tau < \tau^{b1}$, where τ^{b1} is defined in (C.4), it is not profitable to install renewable capacity. Domestic thermal runs at full capacity in state w, and imported electricity is the marginal generation technology, $q_m^w = K_t$. Therefore, $p^w = m+t+\tau$. The zero profit condition of thermal power leads to $p^{\overline{w}} = c+\tau+\frac{r_f - \nu(m+t-c)}{1-\nu}$. So $p = c+\tau+r_f$. Emissions from domestic electricity consumption is $E = K_f + K_t = D(p)$. This case is similar to case (a) in Proposition 1, the only difference is the equilibrium wholesale prices.

Case (b1): When $\tau^{b1} < \tau < \tau^{c1}$, where τ^{c1} is defined in (C.5), it is profitable to invest in renewable capacity up to $K_i = \bar{K}F(\nu(m+t+\tau))$. The dispatch in state w is first domestic thermal power up to K_f, renewables up to K_i, and imported electricity that meets the market clearing condition $q_m^w = D(p) - K_i - K_f < K_t$. The equilibrium wholesale price in state w is $p^w = m + t + \tau$, and the zero profit condition of thermal yields $p^{\bar{w}} = c + \tau + \frac{r_f - \nu(m+t-c)}{1-\nu}$, and $p = c + \tau + r_f$. Emissions from domestic electricity consumption is $E = \nu(K_f + q_m^w) + (1-\nu)(K_f + K_t) = D(p) - \nu K_i$.

Case (c1): When $\tau^{c1} < \tau < \tau^{e1}$, where τ^{k1} is defined in (C.6), renewables and domestic thermal are the only energy source in state w. $K_i = K_t$ crowds out imported electricity $q_m^w = 0$, and $p^w = \frac{\tilde{r}_i^{c1}}{\nu}$, where $\bar{K}F(\tilde{r}_i^{c1}) = K_t$. The zero profit condition of thermal yields $p^{\bar{w}} = \frac{c+\tau+r_f-\tilde{r}_i^{c1}}{1-\nu}$, and $p = c + \tau + r_f$. Emissions from domestic electricity consumption is $E = \nu K_f + (1-\nu)(K_f - K_t) = D(p) - \nu K_t$.

Case (e1): When $\tau^{e1} < \tau < \tau^{f1}$, where τ^{f1} is defined in (C.7), it is profitable to invest in renewable capacity such that the marginal unit has the capacity cost $\nu(c+\tau)$, i.e., $K_i = \bar{K}F(\nu(c+\tau))$. In state w, domestic thermal complements renewables, $q_f^w = D(p) - K_i$ and no electricity import $q_m^w = 0$. $p^w = c + \tau$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$. Emissions is $E = \nu(D(p) - K_i) + (1-\nu)(K_f + K_t) = D(p) - \nu K_i$.

C.4 Proof of Proposition 4

Consider a subsidy rate on renewable capacity s such that $\underline{r}_i - \nu c < s < \underline{r}_i - \nu(m+t)$. Such a subsidy rate makes some renewable capacity cheaper than domestic thermal power when carbon price is zero, but is still more expensive than imported power.

Case (b2): If $\tau < \tau^{c2}$, where τ^{c2} is defined in (C.8) such that renewables and imported electricity are sufficient to meet domestic demand, the renewable producers build capacity up to $\frac{\tilde{r}_i - s}{\nu} = c + \tau$. The merit order in state w is thus imported electricity, renewables, and domestic thermal (assuming $m + t < c$). The wholesale prices are $p^w = c + \tau$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, and the retail price is $p = c + \tau + r_f$. We obtain the following capacities and production level: $K_i = \bar{K}F(\nu(c+\tau) + s)$, $K_f = D(p) - K_t$, $q_f^w = D(p) - K_t - K_i$, $q_m^w = q_m^{\bar{w}} = K_t$. The emissions for electricity consumed is $E = D(p) - \nu K_i$.

Case (c2): If $\tau^{c2} < \tau < \tau^{e2}$, where τ^{e2} is defined in (C.9), renewable capacity is maintained at $K_i = \bar{K}F(\tilde{r}_i) = D(p) - K_t$ as the carbon price increases. The wholesale price $p^w = \frac{\tilde{r}_i - s}{\nu}$ and $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$. Therefore, increasing the subsidy rate decreases the wholesale price and increases consumption since $p = \tilde{r}_i - s + (1-\nu)(c+\tau) + r_f$. $K_f = D(p) - K_t$, $q_f^w = 0$, $q_m^w = q_m^{\overline{w}} = K_t$. The carbon footprint is $E = (1-\nu)D(p) + \nu K_t$, since there is zero domestic emission in state w.

Case (e2): If $\tau^{e2} < \tau < \tau^{f2}$, where τ^{f2} is defined in (C.10), renewable capacity increases such that the marginal capacity has the same cost of as imported electricity ($\frac{\tilde{r}_i - s}{\nu} = m + t + \tau$). In state w, the transmission line is used under capacity with $q_m^w = D(p) - K_i$. The wholesale price is determined by imported electricity at $p^w = m + t + \tau$. The retail price is $p = \nu(m + t + \tau) + (1-\nu)(c+\tau) + r_f$. The total emission from domestic consumption is $E = \nu q_m^w + (1-\nu)D(p) = \nu(D(p) - K_i) + (1-\nu)D(p) = D(p) - \nu K_i$.

Case (f2): If $\tau^{f2} < \tau < \tau^h$, where τ^h is defined in (C.11), renewable capacity is sufficient to meet domestic demand in state w, but is not competitive in the foreign market. Thus $K_i = D(p)$ and crowds out import in state w. The wholesale price in state w is $p^w = \frac{\tilde{r}_i^{f2} - s}{\nu}$, where where $\tilde{r}_i^{f2}$ is defined by $\bar{K}F(\tilde{r}_i^{f2}) = D(\tilde{r}_i^{f2} - s + (1-\nu)(c+\tau) + r_f)$. Thus, $p = \tilde{r}_i^{f2} - s + (1-\nu)(c+\tau) + r_f$. There is no import or export in state w ($q_m^w = 0$). Emissions from domestic consumption is $E = (1-\nu)D(p)$.

Case (h): If $\tau^h < \tau < \tau^{g1}$, where τ^{g1} is defined in (C.12), renewable is competitive in the foreign market and can be exported in state w ($\frac{\tilde{r}_i - s}{\nu} = m - t$). In state w, the flow of trade is from the domestic market to the foreign market at a level below the transmission capacity $q_m^w = D(p) - K_i$. The wholesale prices are $p^w = m - t$, $p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}$, and the retail price is thus $p = \nu(m-t) + (1-\nu)(c+\tau) + r_f$. As the carbon price increases, domestic demand decreases as the retail price increases and there is more excess renewables for export. Although emissions from domestic consumption is still $E = (1-\nu)D(p)$, renewable export lowers foreign emissions by $\nu(K_i - D(p))$.

Case (g1): If $\tau^{g1} < \tau < \tau^k$, where τ^k is defined in (C.13), we have a case similar to

Case (h) except that there is no domestic thermal capacity. As carbon price increases, wholesale price in state $\overline{w}$ increases through CBAM. $p^w = m - t$, $p^{\overline{w}} = m + t + \tau$, and $p = \nu(m-t)+(1-\nu)(m+t+\tau)$, with $\frac{\partial p}{\partial \tau} > 0$. Renewable export in state w is lower than the transmission capacity, $q_m^w = K_i - D(p) < K_t$. Imported electricity is lower than K_t in state $\overline{w}$ with $q_m^{\overline{w}} = D(p)$. Emissions for domestic consumption is thus $E = (1-\nu)D(p)$ and renewable export lowers foreign emissions by $e^f = \nu(K_i - D(p))$.
Case (k): If $\tau > \tau^k$, we have a case similar to Case (g1) except that renewable export is capped at K_t. $p^w = \frac{\tilde{r}_i^k - s}{\nu}$, $p^{\overline{w}} = m + t + \tau$, and $p = \tilde{r}_i^k - s + (1-\nu)(m+t+\tau)$, where $\tilde{r}_i^k$ is defined by $\bar{K}F(\tilde{r}_i^k) = D(\tilde{r}_i^k - s + (1-\nu)(m+t+\tau)) + K_t$. Domestic consumption carbon footprint is $E = (1-\nu)D(p)$ and exported renewables lowers foreign emissions by νK_t.

D Proof of Proposition 5

When the TSO is remunerated with transmission rights, then $t = 0$. With non-competitive renewables (Proposition 1), the first-order condition (11) writes:

$$c + r_f + \tau - m = C_t'(K_t) \quad \text{for } \tau \leq \tau^c, \tag{D.1}$$

and

$$\tilde{r}_i^c + (1-\nu)(c+\tau) + r_f - m = C_t'(K_t) \quad \text{for } \tau^c < \tau < \tau^d. \tag{D.2}$$

Differentiating equations (D.1) and (D.2) with respect to τ shows that K_t is increasing with τ.

If there is a CBAM (Proposition 2 and 3), when the transmission lines are congested in both states, the first-order conditions for the expected profit (13) are

$$c + r_f - m = C_t'(K_t), \tag{D.3}$$

for $\tau \leq \tau^c$ and $\tau \leq \tau^{a1}$ for Propositions 2 and 3, respectively.

When the transmission lines are only congested in state $\overline{w}$ (cases (e) and (f) in Proposition 2, and cases (b1), (c1), and (e1) in Proposition 3), the first-order condition (14) writes

$$(1-\nu)(c-m) + r_f = C_t'(K_t) \quad \text{for } \tau^e < \tau < \tau^g \text{ and } \tau^{e1} < \tau < \tau^{f1}, \tag{D.4}$$

$$c - m + r_f = C_t'(K_t) \quad \text{for } \tau^{b1} < \tau < \tau^{c1}, \tag{D.5}$$

and

$$c + r_f + \nu\tau - \tilde{r}_i^{c1} - (1-\nu)m = C_t'(K_t) \quad \text{for } \tau^{c1} < \tau < \tau^{e1}. \tag{D.6}$$

Differentiating equations (D.3) and (D.5) with respect to τ shows that K_t does not change with τ. However, K_t increases with τ in equation (D.6) (because $\frac{\partial \tilde{r}_i^{c1}}{\partial \tau} = 0$).

E More reliable renewables

With a renewable generation αK_i in state $\overline{w}$, the market-clearing condition (3) becomes:

$$\alpha K_i + K_f + q_m^{\overline{w}} = D(p). \tag{E.1}$$

The zero-profit condition per kWh that defines the threshold renewable cost of the less profitable producer denoted $\tilde{r}_i^{\alpha}$ writes:

$$\nu p^w + (1-\nu)\alpha p^{\overline{w}} = \tilde{r}_{i,\alpha} \tag{E.2}$$

With the equilibrium prices in case (b) of Proposition 1, we obtain:

$$\tilde{r}_{i,\alpha}^b = (c+\tau)[\nu + \alpha(1-\nu)] + \alpha r_f \tag{E.3}$$

The threshold carbon price τ_α^b for which renewables become competitive can be found by equalizing $\tilde{r}_{i,\alpha}^b$ with $\underline{r}_i$, which yields:

$$\tau_\alpha^b = \frac{\underline{r}_i - \alpha r_f}{\nu + \alpha(1-\nu)} - c. \tag{E.4}$$

Comparing (E.4) with (B.1) shows that $\tau_\alpha^b < \tau^b$ whenever $\alpha > 0$. Furthermore, $\tilde{r}_{i,\alpha}^b - \tilde{r}_i = \alpha[(1-\nu)(c+\tau)+r_f] > 0$. Hence, the renewable capacity $K_i = \bar{K}(\tilde{r}_{i,\alpha}^b)$ is increasing with α for a given carbon price τ: more renewables are installed when their availability increase in state $\bar{w}$ in case (b) of Proposition 1. Using the market clearing condition (E.1), we can obtain $K_f = D(p) - K_t - \alpha K_i$, which is lower compared to the (b) of Proposition 1. Having reliable renewables crowds out domestic thermal capacity and reduces emissions in state $\bar{w}$.

The threshold carbon price τ_α^c between cases (b) and (c) in Proposition 1 can be found with the market clearing condition (2) with the case (b) equilibrium prices and the threshold cost $\tilde{r}_{i,\alpha}^b$ defined in (E.2), that is:

$$\bar{K}F\left((c+\tau_\alpha^c)[\nu + \alpha(1-\nu)] + \alpha r_f\right) + K_t = D\left(c + r_f + \tau_\alpha^c\right). \tag{E.5}$$

Comparing (E.5) with (B.2) shows that $\tau_\alpha^c < \tau^c$ for all $\alpha > 0$ as the the LHS of (E.5) is greater than the LHS of (B.2) for all τ. When $\tau > \tau_\alpha^c$, the zero-profit condition of the least profitable renewable unit yields $p^w = \frac{1}{\nu}(\tilde{r}_{i,\alpha}^c - \alpha[(c+\tau)(1-\nu) + r_f])$, where $\tilde{r}_{i,\alpha}^c$ is defined by

$$\bar{K}F(\tilde{r}_{i,\alpha}^c) + K_t = D(\tilde{r}_{i,\alpha}^c + (1-\alpha)[(c+\tau)(1-\nu) + r_f]). \tag{E.6}$$

Comparing (E.6) to (B.10), we can conclude that $\tilde{r}_{i,\alpha}^c > \tilde{r}_i^c$, similar to case (b). Substituting $q_w^f = 0$ and $q_m^w = q_m^{\bar{w}} = K_t$ in the market clearing conditions (2) and (E.1) and combining them yields $K_f = (1-\alpha)K_i$ which links renewable and thermal capacity in case (c) of Proposition 1 where the two energy sources are complement. The consumption level is also increasing in α in case (c).

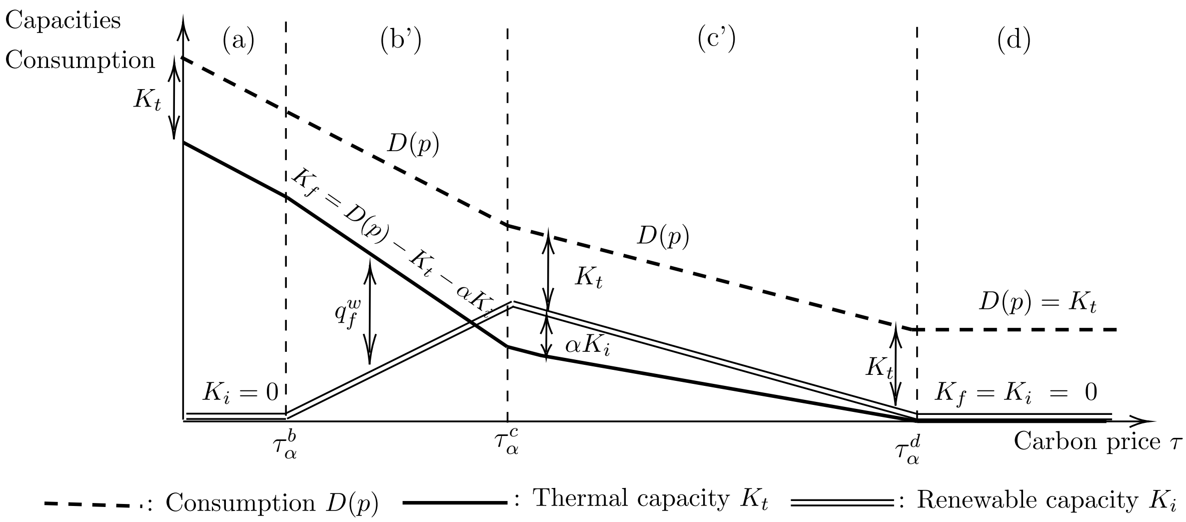
The threshold carbon price τ_α^d between cases (c) and (d) in Proposition 1 is defined by:

$$K_t = D\left(\tilde{r}_{i,\alpha}^c + (1-\alpha)[(c+\tau_\alpha^d)(1-\nu)+r_f]\right), \tag{E.7}$$

where $\tilde{r}_{i,\alpha}^c$ is defined as in (E.6). Compared to (B.3), we find that $\tau_\alpha^d > \tau^d$, that is the threshold carbon price for electricity to be fully imported is higher with reliable renewables. The energy mix in case (d) remains unchanged.

Figure E.1 illustrates the equilibrium energy mix with more reliable renewables.

Figure E.1: Energy mix with non-competitive and more reliable renewables



In the case of CBAM with reliable renewables, CBAM changes the merit order of dispatch at higher carbon prices. Assuming $m + t < \min\{\frac{\tilde{r}_i}{\nu}, c\}$ as in Proposition 2, cases (a), (b') and (c') are the same as in Figure E.1. There exists a threshold τ_α^e such that the capacity cost of the least efficient renewables is the same as imported electricity with a carbon tariff τ. τ_α^e is defined by

$$\bar{K}F\left(\tilde{r}_{i,\alpha}^e\right) + K_t = D\left(\nu(m+t) + (1-\nu)c + \tau_\alpha^e + r_f\right), \tag{E.8}$$

where

$$\tilde{r}_{i,\alpha}^k = \nu(m+t+\tau) + \alpha[(1-\nu)(c+\tau)+r_f]. \tag{E.9}$$

Comparing (E.8) to (C.1), we can show that $\tau_\alpha^e < \tau^e$ for $\alpha > 0$. In case (e') as shown in Figure E.2, the market cleaning condition in state w determines the import electricity level $q_m^w = D(p) - \bar{K}F(\tilde{r}_{i,\alpha}^e)$ where $\tilde{r}_{i,\alpha}^e$ is defined as in (E.9). For a given carbon price , $\tilde{r}_{i,\alpha}^e > \tilde{r}_i^e$ and, therefore, renewable capacity K_i is higher with more reliable renewables. The market clearing condition in state $\overline{w}$ then determines $K_f = D(p) - K_t - \alpha K_i$. The retail and wholesale prices are the same as in case (e) of Proposition 2 and are not affected by renewable reliability α.

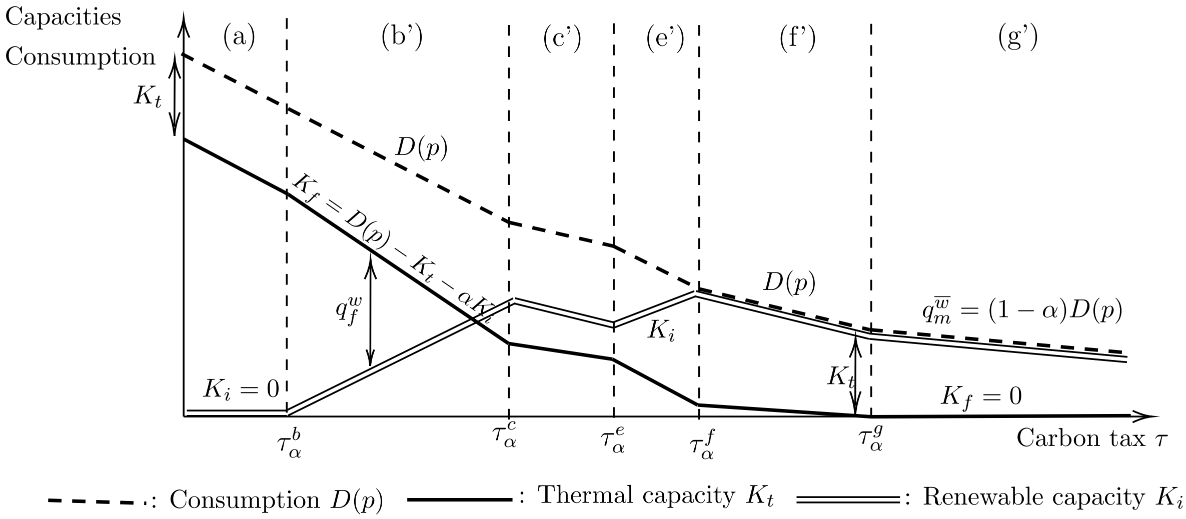
For $\tau > \tau_\alpha^e$, the reliability parameter α maybe such that thermal power or imports are not anymore needed in state $\overline{w}$. Otherwise, there exists a threshold carbon price τ_α^f is defined by

$$\bar{K}F\left(\nu(m+t+\tau_\alpha^f)+\alpha[(1-\nu)(c+\tau_\alpha^f)+r_f]\right)=D\left(\nu(m+t)+(1-\nu)c+\tau_\alpha^f+r_f\right). \tag{E.10}$$

Compare (E.10) to (C.2), we get $\tau_\alpha^f < \tau^f$. That is renewable capacity is sufficient to meet domestic demand in state w at a lower carbon price with reliable renewables.

In case (f'), the retail price decreases with α so that the demand is higher. Therefore, the threshold τ_α^g is higher than τ_g. In case (g'), renewables crowd out import in state $\overline{w}$ such that $q_m^{\overline{w}} = (1-\alpha)D(p)$.

Figure E.2: Energy mix with non-competitive and more reliable renewables under CBAM



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