Electricity Interconnection with Intermittent Renewables*

Yuting YANG†

November 26, 2019

Abstract

Electricity interconnection has been recognized as a way to mitigate carbon emissions by dispatching more efficient electricity production and accommodating the growing share of renewables. I analyze the impact of electricity interconnection in the presence of intermittent renewables, such as wind and solar power, on renewable capacity and carbon emissions using a two-country model. I find that in the first-best, interconnection decreases investments in renewable capacity and exacerbates carbon emissions if the social cost of carbon (SCC) is low. Conversely, interconnection increases renewable capacity and reduces carbon emissions for a high SCC. Moreover, the intermittency of renewables generates an insurance gain from interconnection, which also implies that some renewable capacity is optimally curtailed in some states of nature when the SCC is high. The curtailment rate and the corresponding carbon emissions increase for more positively correlated intermittency. I calibrate the model using data from the European Union electricity market and simulate the outcome of expanding interconnection between Germany-Poland and France-Spain. I find that given the current level of SCC, the interconnection may increase carbon emissions. The net benefit of interconnection is positive, with uneven distribution across countries.

Keywords: Intermittent renewables, electricity interconnection, trade and environment, carbon emissions.

JEL Classification: D24, D61, F18, F61, Q27, Q48, Q54

*I would like to thank Stefan Ambec, Christopher Costello, Alexandre de Cornière, Olivier Deschenes, Alexander Guembel, James Hammitt, Christian Hellwig, Kelsey Jack, Stefan Lamp, Levi Marks, Kyle Meng, Sophie Moinas, Knut Einar Rosendahl, Derek Strong, Nicolas Treich, as well as the participants at the TSE energy workshop, EAERE and EAAERE conferences and seminars in TSE and UCSB for useful comments and suggestions. This research was supported by the H2020-MSCA-RISE project GEMCLIME-2020 GA No. 681228.

†Toulouse School of Economics. Email: yuting.yang@tse-fr.eu

1 Introduction

Renewable energy plays an essential role in decarbonizing the power sector. The International Energy Agency (IEA) projects that global renewable capacity will grow by over 50% by 2023 (IEA 2018). Intermittent energy sources that come on and off depending on the prevailing weather conditions, such as wind or solar energy, account for more than 80% of this growth. The intermittency imposes risks on the power system, which must instantaneously balance supply and demand at all times. Electricity interconnection, or cross-border transmission, is recognized as one of the solutions to this issue (Bahar and Sauvage 2013).[1]

Electricity interconnection allows for the international exchange of electricity. This trade opportunity has several established benefits. First, similar to other tradable goods, international trade harnesses varying comparative advantages in electricity production across countries, which can lower prices to consumers through improved production efficiency. Second, trade can facilitate the penetration of renewables to regions with insufficient renewable resources or technology, thereby enhancing the potential to lower carbon dioxide (CO_2) emissions. A third benefit that is unique to electricity trading, especially in the case of uncertainty associated with renewable production, is the additional motive of insuring against local supply shocks.[2] In particular, interconnection can serve as a backup for renewables with the importation of controllable thermal energy (e.g. coal, gas) constantly available to generate power, or it can utilize the imperfect correlation of renewable production across space.

The potential benefits on top of the infrastructural cost have led governments to expand electricity interconnection. The European Commission is implementing a policy to increase electricity interconnection from the current level of less than 10% to 15% of the total installed capacity by 2030 (European Commission 2018). China, Japan, South Korea, Russia, and Mongolia have also been working together to construct the Asia Super Grid (ASG), which would utilize the abundant renewable resources in Mongolia and drastically reduce carbon emissions (Mano et al. 2014). With the potential implementations of interconnection policies, we now need more than ever to understand how interconnection affects the adoption of technologies and capacity investment. More importantly, can these policies always deliver positive outcomes in response to climate change?

[1] Other ways to solve the problem of intermittency include demand-side responses and grid-level storage facilities. For example, Moura and De Almeida (2010) analyze the impact of demand-side management and demand response on the integration of the growing intermittent resources in Portugal. Suberu et al. (2014) review different energy storage systems and their advantage in mitigating intermittency. In this paper, I focus the analysis only on interconnection.

[2] Antweiler (2016) is the first to build a model of two-way electricity trade and refers to the insurance motive as "reciprocal load smoothing" for stochastic demand variations.

To answer this question, I construct a two-country model of optimal electricity production with renewable intermittency and trade. Each country can be either a Clean type (that has both fully controllable thermal and intermittent renewable technology) or a Dirty type (that has only thermal technology). The countries coordinate by choosing their consumption levels, installed capacities, and state-dependent output levels and trade quantities so their joint social welfare is maximized. This model captures all of the interconnection benefits and allows me to identify additional trade-offs in interconnection regarding renewable capacity and carbon emissions.

Several takeaways arise from the theoretical analysis. First, consider the case where the two interconnected countries are of one Clean and one Dirty type, and the Dirty country has an absolute advantage over thermal production. In this case, expanding interconnection has ambiguous effects on carbon emissions, depending on the level of the social cost of carbon (SCC). If the SCC is low (high), interconnection exacerbates (reduces) carbon emissions. The intuition lies in the fact that transmission is a two-way street and facilitates not only renewable diffusion when the wind is blowing, or the sun is shining, but also the dispersion of cheaper thermal production when generation backup is needed. With a low SCC, interconnection gives the Clean country access to a lower-cost thermal technology, which would decrease its adoption of renewables (reverse technique effect). In addition, the optimal consumption in the Clean country increases with opening up, because of the cheaper backup thermal energy (scale effect). Both the scale and the reverse technique effect push emissions upward. However, with a high SCC, interconnection expands the market of Clean country renewables, which are now less costly than thermal energy (technique effect). The technique effect and scale effect take opposite directions, and depending on which effect dominates, emissions can increase or decrease.

Second, if both countries are of the Clean type and differ only in the occurrence of the intermittent states, renewable curtailment, i.e., having idle renewable capacity or disposing of renewable generated electricity, may be optimal in some states. Interconnection kicks in as insurance against intermittency when the wind in one country dies and is still blowing in the other country. For the country in which the wind is still blowing to export electricity, they must have a renewable capacity exceeding local demand. This excess supply becomes idle when the wind is blowing in both countries. The curtailment rate and the corresponding carbon emissions depend positively on the correlation of occurrence of their windy states. The more positively correlated, the more likely some capacity stays idle and the higher the carbon emissions, all else being equal. Therefore, not allowing for curtailment reduces the capacity that can be installed, undermining any insurance motive of interconnection, and trade will not take place in any state of nature.

To quantify the scale of the effect from the theoretical model, I simulate the Germany-Poland (DE-PL) and France-Spain (FR-ES) interconnections to represent the Clean-Dirty and Clean-Clean case, respectively. For the FR-ES interconnection, I also simulate FR wind-ES wind and FR wind-ES solar separately, to explore the effect of intermittency correlation. The four countries represent four distinctive energy profiles: Germany has various types of coal and renewables; Poland is predominantly powered by coal; France has over 70% nuclear with gas and wind power; and Spain has a mix of nuclear, thermal, and renewables. The four countries are also geographically connected and have existing transmission lines in use. Therefore, understanding the impact of existing transmission capacity is important in the representative European Union (EU) context. Moreover, the simulation results can be generalized to any country or region with a similar energy profile.

Simulation results show that achieving the EU's 2030 interconnection target under an SCC of €45 per ton of CO_2 increases annual emission by 1.69% in the DE-PL case, by 1.74% in the FR wind-ES wind case, and reduces emission by 7.18% in the FR wind-ES solar case, all in comparison with the status quo. Compared to the binding target of cutting emission by 43% in the EU power sector by 2030, interconnection can contribute a range from -5 to 23% of the target. I then conduct a benefit-cost analysis (BCA) for expanding interconnection capacities. The BCA shows that although transmission lines require a high upfront investment, the life-time benefit outweighs the cost. However, the net benefit is unevenly distributed across countries. For instance, in the DE-PL case, Germany obtains 100% of the net gain from a 5300 MW interconnection and Poland acquires none. The net importer (Germany) captures all the net benefit because of its increased consumer surplus and avoided investment cost of wind capacity. This uneven distribution could shed light on how the interconnection investment cost should be shared.

This paper contributes to several strands of literature. The most related is the growing theoretical literature on electricity production with intermittent renewables. Ambec and Crampes (2012) construct a model which characterizes the optimal energy mix between the controllable source and the intermittent source and analyze the market structure to decentralize the optimal mix. The literature also analyzes issues including how different policy instruments, demand-side response, and storage technology affect the optimal energy mix with renewable intermittency (Ambec and Crampes 2012; 2019, Helm and Mier 2019). However, the literature has ignored issues related to electricity transportation and distribution in energy transmission, i.e., congestion and grid design. This paper builds on the model of Ambec and Crampes (2012; 2019) to consider how electricity interconnection affects the optimal energy mix, and consequently its effect on carbon emissions.

This paper is also related to the theoretical literature on electricity transmission. Joskow and Tirole (2000; 2005) consider an electricity transmission model and study how the allocation of transmission rights affects market power and investment incentives on transmission lines. In the absence of intermittency, the trade flow always goes in one direction in equilibrium. I consider transmission with intermittent renewables which leads to reciprocal trading. Other theoretical models that study the gains from electricity trade consider stochastic demand (Antweiler 2016) or seasonal supply variations (Von Der Fehr and Sandsbråten 1997).[3] In these papers, the gains from electricity trade are on the intensive margin as production capacities are exogenous. In contrast, I endogenize capacities to also look at the extensive marginal gains from trade with particular attention given to renewable penetration. There is also a growing empirical literature on estimating the gains from electricity trade and the social value of renewables (Abrell and Rausch 2016; Cullen 2013; Gowrisankaran et al. 2016; LaRiviere and Lu 2018). This paper supplements the literature by identifying the key determinants of the social value of trade with intermittent renewables.

Moreover, this paper contributes to the extensive literature on the effect of trade on the environment. Openness to the international goods market can have a direct and indirect impact on a country's environment. Antweiler et al. (2001) is the first to provide a theoretical framework that decomposes the impact of trade on the environment into a scale, technique, and composition effect. Depending on the environmental aspect (e.g., pollution, biodiversity) and countries, empirical estimates of the overall effect can be either positive or negative (Antweiler et al. 2001; Copeland and Taylor 2004; Curtis et al. 2014; Hauch 2003; Managi et al. 2009; WTO-UNEP 2009). This paper fits into this literature by decomposing the scale and technique effect of electricity trading on carbon emissions.[4] The calibrated simulation also provides suggestive evidence on the magnitude of the effects.

The paper proceeds as follows. Section 2 describes the model setup. Section 3 presents the benchmark case of countries under autarky. Section 4 provides a theoretical analysis of the Clean-Dirty and Clean-Clean interconnection in the first-best. Section 5 presents the calibrated simulation exercise and benefit-cost analysis, and Section 6 provides a final overview.

[3] Another way to model renewable intermittency is by looking at the demand net of renewable production. Thus, Antweiler (2016) implicitly models intermittency through demand variations.

[4] There is no composition effect in the case of electricity trading as electricity is a homogeneous good.

2 The Model

I build upon the work of Ambec and Crampes (2012) and Joskow and Tirole (2000) and construct a stylized model of electricity trade. Interconnection takes place between two countries (or regions); each can be of the Clean type (c) or the Dirty type (d). I solve the special case of symmetric countries analytically if they are of the same type. In the simulation, I consider the more general cases of asymmetric countries.

Electricity production

On the supply side, electricity can be generated from two technologies: a fully controllable polluting thermal power f (e.g., coal, gas) and an intermittent clean renewable energy source i (e.g., wind, solar). The Clean country has both technologies available, whereas the Dirty country has only thermal power. The market is fully competitive for both technologies.

For the thermal power, the installed capacity K_{jf} ($j \in \{c, d\}$) has a constant unit capacity cost r_f. The fuel and operational cost of producing q_{jf} kilowatt-hour (kWh) of electricity is κ_j, if it does not exceed the installed capacity. The Dirty country is assumed to have an absolute advantage in thermal production ($\kappa_d < \kappa_c$). The electricity produced by thermal power emits carbon dioxide (CO_2) into the atmosphere. The SCC normalized for each unit of electricity produced is denoted δ.[5] Therefore, the total environmental damage of thermal electricity production is $\delta * q_{jf}$ and the total emission is equal to the total production from the thermal power $E = q_{jf}$.

For the intermittent renewables, the total cost of installing capacity K_i is $f(K_i)$, where f is an increasing and convex function ($f' > 0$, $f'' > 0$). The marginal capacity cost is denoted as $r_i \equiv f'(K_i)$, and $r_i \in [\underline{r}_i, +\infty)$ for $K_i \in [0, \bar{K}]$. The assumption of a convex cost of renewable capacity can be justified by the uneven distribution of wind and solar energy across the terrain of a country. The wind and solar farms are installed first in the areas with the highest wind and solar power density and subsequently installed in locations with a lower hourly yield.The production of renewables depends on the prevailing weather conditions. There are two states of nature $s \in \{l, h\}$ with high (h) and low (l) renewables output. In the high state, renewables can generate output at full capacity, and the marginal production cost is normalized to zero. In the low state, the renewables are inactive, with zero output. The two states occur with the exogenous probabilities ν_j and

[5] The analysis can also be adapted to other pollutants, such as SO_2 and NO_X. However, since these pollutants create local rather than global environmental damages, the social cost is thus localized. The literature on the pollution haven effect (e.g., Copeland and Taylor (1994)) focuses on discussing of local pollutants.

$1-\nu_j$ respectively, which capture the degree of intermittency of the renewables.[6] Note that for the Dirty country $\nu_d = 0$ and for the Clean country $\nu_c = \nu$, $\nu \in (0,1)$.

Across two Clean countries, there are jointly four states of nature as shown in the table below.

	Clean		
Clean	h,h	h,l	ν
	l,h	l,l	$1-\nu$
	ν	$1-\nu$	

The correlation factor of the joint Bernoulli distribution is denoted as $\rho \in [-1,1]$, with $\rho = 1$ indicating perfect positive correlation and $\rho = -1$ for perfect negative correlation. The joint probabilities of the states are thus $\sigma_{hh} = \nu^2 + \rho\nu(1-\nu)$, $\sigma_{hl} = \sigma_{lh} = \nu - \sigma_{hh}$, $\sigma_{ll} = 1 - \nu - \sigma_{hl}$.

Electricity consumption

On the demand side, consumers in each country derive gross utility $S(Q_j)$ from the consumption of Q_j kWh of electricity. $S(\cdot)$ is continuous and twice differentiable with $S' > 0$ and $S'' < 0$. $S'(0)$ is assumed to be large so that it is always efficient to have some electricity consumption. The demand function is $D(p_j) = S'^{-1}(p_j)$, where p_j stands for the retail price in country j. Throughout the paper, I assume that consumers are subject to contracts that do not allow for state-contingent retail prices. Consumers thus have non-state-contingent demand $Q_j^h = Q_j^l$.[7] Moreover, rationing is not allowed; i.e., there can be no partial blackouts. Therefore, the supply must satisfy a constant demand, independent of the state. However, in the wholesale market, price is state-dependent denoted by p_j^s.

Electricity trade

The interconnected countries can import or export electricity up to the capacity limit K_t of the transmission lines. However, at any given time, the net electric current flows in one direction, and the net flow quantity is denoted by x^s ($s \in \{h,l\}$). Throughout the paper, transmission line losses are assumed to be zero.[8] Moreover, I assume that the transmission operation market is perfectly competitive. Thus, electricity is always traded

[6] ν_j can also be interpreted as the load factor of renewable energy production.

[7] In reality, most electricity contracts offered to consumers are with a fixed unit price or a tier-pricing depending on the quantities consumed. The retail price does not change with the spot price on the wholesale market and demand is thus independent of how electricity is produced.

[8] This is without loss of generality as the direction of the results will not be affected, but the scale may be dampened. In the benefit-cost analysis, this assumption is relaxed.

at the wholesale prices.

The social planner solves a two-stage problem. In the first stage, she chooses the thermal and renewable capacities and fixes the retail price for consumers. In the second stage, consumers decide on the consumption level, given the retail prices. Producers bid at marginal cost for electricity generation depending on the realization of the states of nature. The social planner then decides on how much the grid takes from each technology subject to the merit-order effect.[9] Since there is no uncertainty in the probability of the states of nature, the solution for this two-stage problem is equivalent to a static model where the social planner maximizes the expected social welfare. The social planner's objective function for country j is thus:

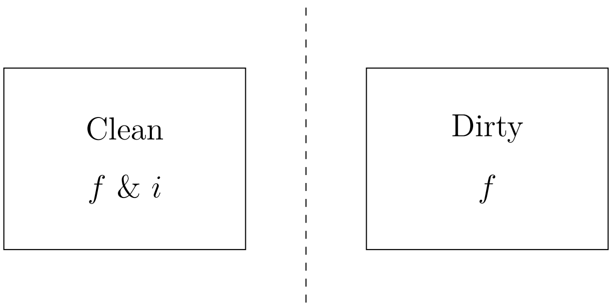
$$W(Q_j, q_{jf}^h, q_{jf}^l, K_{jf}, K_i; \kappa_j, \nu_j) = S(Q_j) - (\kappa_j + \delta)(\nu_j q_{jf}^h + (1-\nu_j) q_{jf}^l) - r_f K_{jf} - f(K_i) \quad (1)$$

Note that the first-best allocation can be decentralized as a competitive market equilibrium, if there is a Pigouvian carbon tax equal to the SCC. The tax allows the thermal producers to fully internalize the social damage of carbon emissions, which in turn restore the first-best.

3 The Autarky Case

As a benchmark, consider that both countries are under autarky (Figure 1) and the social planner solves the welfare maximization problem for each type of country.

Figure 1: Illustration of countries under autarky



For the Clean type, in state h, renewables can be produced at the maximum installed capacity K_i. Given the merit-order effect of electricity dispatch, renewable power is fully fed into the grid since its marginal production cost is zero. Thermal power is also available

[9] The merit-order is the ranking of energy sources by their short-run marginal cost and production capacity. To minimize production cost, the sources with the lowest marginal costs are those first utilized to meet electricity demand (Sensfuß et al. 2008).

as a supplementary source to meet demand. In state l when the wind is not blowing or the sun is not shining, the thermal power kicks in as generation backup. Thus, $Q_c = K_i + q^h_{cf}$ in the state h and $Q_c = q^l_{cf}$ in the state l. Since capacity is costly, an idle capacity that is not used in any state is strictly inefficient. The capacity of thermal power must be equal to its production in the peak state, $K_{cf} = q^l_{cf}$. The social planner chooses Q_c, K_i, K_{cf}, and q^h_{cf} for the Clean type, subject to the non-state-contingent demand and production feasibility constraints.

$$
\begin{aligned}
\max_{Q_c, K_i, K_{cf}, q^h_{cf}} \quad & W(Q_c, q^h_{cf}, K_{cf}, K_i; \kappa_c, \nu) \\
\text{s.t.} \quad & K_i + q^h_{cf} = Q_c \\
& K_{cf} = Q_c \\
& K_{cf} \geq q^h_{cf} \geq 0 \\
& K_i \geq 0
\end{aligned}
\tag{2}
$$

In the Appendix A.1 I derive the following lemma:

Lemma 1. *The optimal installed capacities, production and electricity consumption in the Clean type under autarky (super-scripted A) are*

- *i If $\delta \leq \underline{\delta}_A$, only thermal energy is producing in both states. $q^{hA}_{cf} = K^A_{cf} = Q^A_c = D(\kappa_c + \delta + r_f)$, and $K^A_i = 0$. $\underline{\delta}_A = \frac{r_i}{\nu} - \kappa_c$.*
- *ii If $\underline{\delta}_A < \delta \leq \bar{\delta}^A$, then both thermal and renewables produce in the state h. $K^A_{cf} = Q^A = D(\kappa_c + \delta + r_f)$, $K^A_i = f'^{-1}(\nu(\kappa_c + \delta))$, $q^{hA}_f = Q^A_c - K^A_i$. The threshold $\bar{\delta}^A$ satisfies $f'^{-1}(\nu(\kappa_c + \bar{\delta}^A)) = D(\kappa_c + \bar{\delta}^A + r_f)$.*
- *iii If $\delta > \bar{\delta}^A$, then only renewables produce in the state h. $K^A_{cf} = Q^A_c = D((1-\nu)(\kappa_c + \delta) + \tilde{r}^A_i + r_f)$, $K^A_i = Q^A_c$, and $q^{hA}_{cf} = 0$, where $\tilde{r}^A_i = f'(K^A_i)$.*[10]

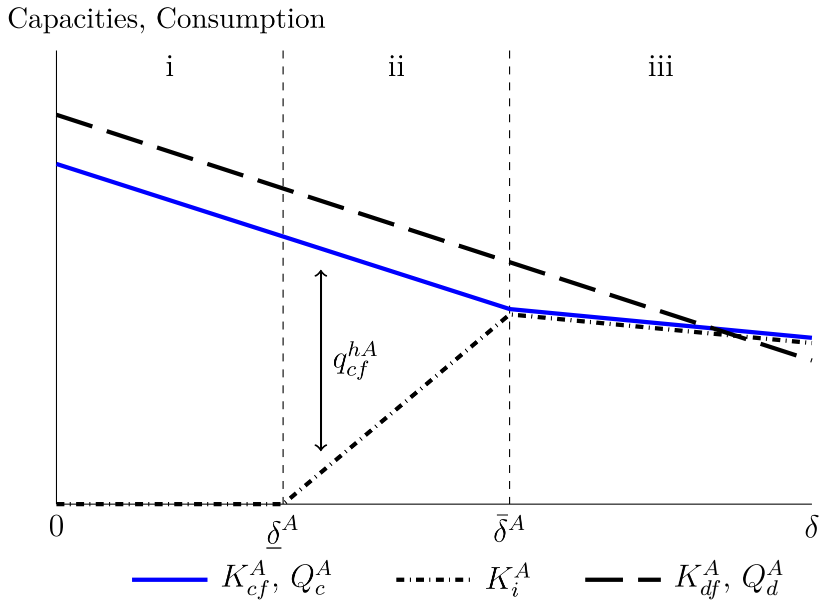
Lemma 1 is similar to Ambec and Crampes (2012, Proposition 1) and is illustrated in Figure 2. The characterization of the first-best optimum critically depends on the SCC.[11] In case i, it is cost-inefficient to have renewable capacity installed. Thermal power runs in both states to meet demand. In case ii, renewable energy is installed but the capacity is lower than the consumption level. Thermal power supplements renewable production in state h. In case iii, renewable production in state h can meet full demand, so the

[10] $\tilde{r}^A_i$ denotes the marginal cost of the least efficient renewable capacity installed.

[11] The threshold conditions can be interpreted in different ways. Throughout this paper, the discussion is focused on the implications of the variation in δ. Analogous interpretations can also be drawn from the perspective of the capacity cost of renewable energy (r_i), the load factor level (ν), or the marginal fuel cost of thermal power (κ).

thermal power is only used as a backup in state l. Consumption in this case is higher than with only thermal power.

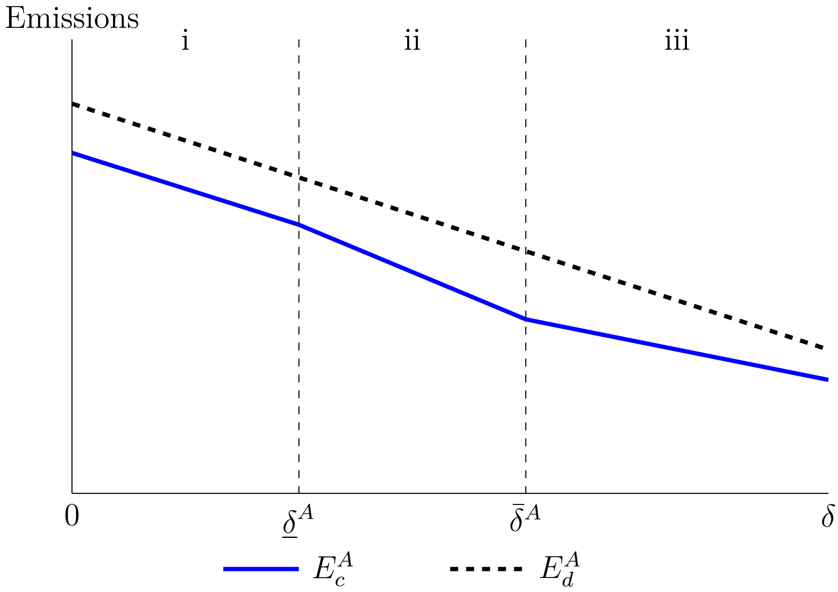
Figure 2: Optimal capacities, production, and consumption under autarky



It can be seen that that in Lemma 1 the optimal consumption equals demand at the retail price equivalent to the expected long-run marginal cost ($p_c = \kappa_c + \delta + r_f$ in case i and ii, and $p_c = (1-\nu)(\kappa_c + \delta) + \tilde{r}_i^A + r_f$ in case iii). Thus the market-clearing price in each state should be equal to the long-run marginal cost ($p_c^h = \kappa_c + \delta$ in case i and ii, and $p_c^h = \frac{\tilde{r}_i^A}{\nu}$ in case iii; and $p_c^l = \kappa_c + \delta + \frac{r_f}{1-\nu}$). p_c^h and p_c^l yield the familiar off-peak and peak prices from the peak-load pricing literature (Williamson 1966). In state h, renewables are at their peak and thermal is at its off-peak, whereas in state l, thermal energy is at its peak. Therefore, with a Pigouvian carbon tax equal to the SCC, the state-contingent prices p_c^h and p_c^l can implement the first-best energy mix.

For the Clean type, the expected carbon emissions follow directly from Lemma 1 and are illustrated in Figure 3. In case i, emissions are one to one with consumption. In case ii, with the joint operation of renewables and thermal energy in state h, the emissions are consumption net of the partial renewable production in state h. In case iii, emissions accounts only for the consumption in state l.

Figure 3: Carbon emissions under autarky



The Dirty type, with only thermal power, has no problem of intermittency. Essentially, its maximization problem is a special case of the problem of the Clean type, with $\nu_d = 0$ and $K_i = 0$. The optimal thermal capacity and consumption level are analogous to case i of of Lemma 1 and is illustrated in Figure 2.

Note that the Dirty type has a higher optimal consumption level than the Clean type, given its cost advantage in thermal production. However, this cost advantage diminishes for a high SCC, as the consumption in the Clean country decreases at a slower rate with respect to the SCC.

4 Electricity Interconnection

In this section, I consider electricity interconnection between two countries. More specifically, I separate two cases: Clean-Dirty interconnection and Clean-Clean interconnection.[12] This separation is justified by the inherent differences in the national energy mix across countries. For example, over 80% of Poland's electricity is generated from coal, and Germany has a mix of nuclear, coal, gas, and renewables. France's electricity is predominantly generated by nuclear power, supplemented by gas and renewables, and Spain has an even mix of wind, solar and gas. Therefore, connecting Germany and Poland may have implications that differ from connecting France and Spain. By analyzing the two

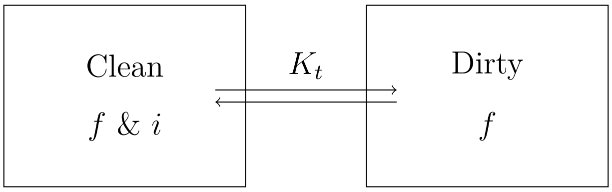
[12] The case of Dirty-Dirty interconnection is not interesting under the assumption of symmetric types. Trade will not take place since there is no comparative advantage in either country.

cases separately, the characteristics of renewable generation, namely intermittency and imperfect correlation, can be made more salient.

4.1 The Clean-Dirty interconnection

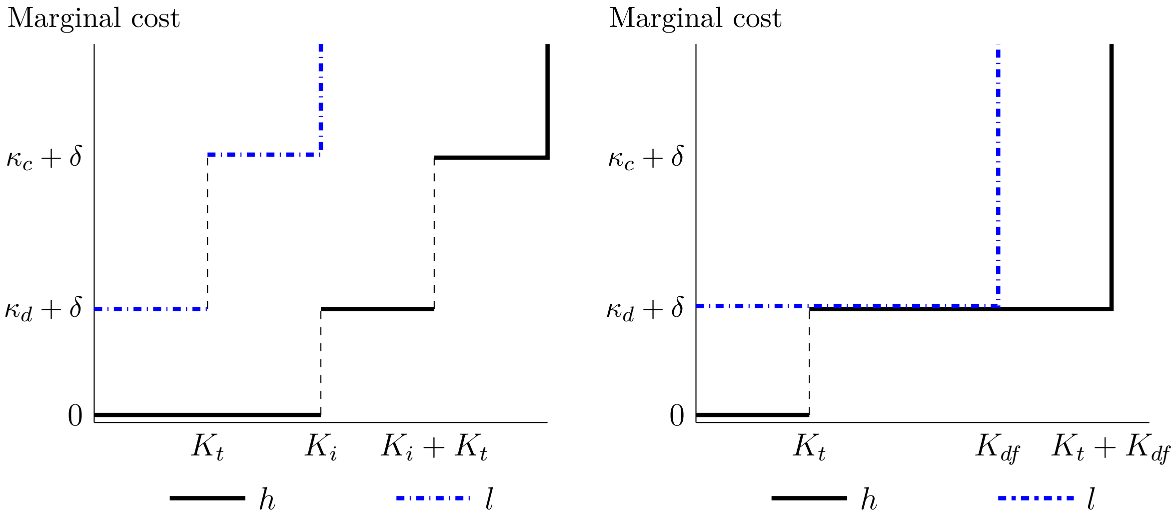
In the case of Clean-Dirty interconnection (Figure 4), trade affects the two countries in different ways. For the Clean country, it now has access to a cheaper backup thermal power. For the Dirty country, it can potentially import clean electricity in state h. The Dirty country is now indirectly intermittent because of trade.

Figure 4: Illustration of electricity interconnection between a Clean and a Dirty country



The merit order in each country changes depending on the production availability in each state, and the exogenous transmission constraint K_t, as shown in Figure 5. In state h, the Clean country first dispatches the renewable generation at marginal cost 0 up to the renewable capacity K_i. Then it dispatches the cheaper thermal power imported from the Dirty country up to the transmission constraint K_t at a marginal cost $\kappa_d + \delta$. Its thermal production meets the residual demand at a marginal cost $\kappa_c + \delta$. Analogies can be made for state l and the Dirty country. Note that no country can simultaneously import and export in a given state.

Figure 5: Merit order of the Clean and Dirty interconnection



(a) Clean **(b)** Dirty

With interconnection, the social planner maximizes the joint social welfare choosing the optimal levels of consumption Q_j, production q^h_{jf}, capacities K_{jf}, K_i and trading quantities x^s for both countries.[13] Compared to the autarky setting, demand in each country is now satisfied with their own country's production net of trade. In state l, electricity always flows from Dirty to Clean since $\kappa_d < \kappa_c$. In state h, the trade flow can be in either direction depending on whether excess renewable capacity is available. The transmission capacity caps the quantity traded. The first-best maximization problem is solved subject to the non-state-contingent demand, production feasibility, and transmission capacity constraints.

$$\begin{aligned}
\max_{\substack{Q_j, K_{jf}, q^h_{jf}, K_i, x^s \\ j\in\{c,d\}, s\in\{h,l\}}} \quad & W(Q_c, q^h_{cf}, K_{cf}, K_i; \kappa_c, \nu) + W(Q_d, q^h_{df}, K_{df}; \kappa_d, \nu) \\
\text{s.t.} \quad & K_i + q^h_{cf} - x^h = Q_c \\
& K_{cf} + x^l = Q_c \\
& q^h_{df} + x^h = Q_d \\
& K_{df} - x^l = Q_d \\
& 0 \leq q^h_{jf} \leq K_{jf} \quad \forall j \in \{c,d\} \\
& K_i \geq 0 \\
& -\min\{K_t, Q_c\} \leq x^h \leq \min\{K_t, Q_d\} \\
& x^l \leq \min\{K_t, Q_c\}
\end{aligned} \tag{3}$$

In the Appendix A.2 I derive the following lemma:[14]

Lemma 2. *(Free trade optimality) The optimal installed capacities, production and electricity consumption in the Clean and Dirty country when K_t is not binding (super-scripted F) are*

i If $\delta \leq \underline{\delta}^F$, the Dirty country produces with thermal power in both states. $Q^F_c = Q^F_d = D(\kappa_d + \delta + r_f)$, $K^F_{df} = q^{hF}_{df} = Q^F_c + Q^F_d$, $q^{hF}_{cf} = K^F_{cf} = 0$, and $K^F_i = 0$. $\underline{\delta}^F = \frac{r_i}{\nu} - \kappa_d$. Trade flow in both states are from Dirty to Clean and equal Q^F_c.

ii If $\underline{\delta}^F < \delta \leq \bar{\delta}^F$, the Clean country produces with renewables and the Dirty country supplements the production with thermal power in state h. Also, the Dirty country produces with full thermal capacity in state l. $Q^F_c = Q^F_d = D(\kappa_d + \delta + r_f)$, $K^F_{df} = Q^F_c + Q^F_d$, $K^F_i = f'^{-1}(\nu(\kappa_d + \delta))$, $q^{hF}_{df} = K^F_{df} - K^F_i$, and $q^{hF}_{cf} = K^F_{cf} = 0$. The threshold $\bar{\delta}^F$ satisfies $f'^{-1}(\nu(\kappa_d + \bar{\delta}^F)) = 2D(\kappa_d + \bar{\delta}^F + r_f)$. The trade flow in state h can be in either direction and $x^h = K_i - Q_c$.

[13] Recall that $q^h_{jf} = K_{jf}$ holds even with trade.

[14] The full analysis for constrained transmission is in Appendix A.8.

iii *If $\delta > \bar{\delta}^F$, then only the Clean country produces with renewables in state h, and the Dirty country produces only in state l. $Q_c^F = Q_d^F = D((1-\nu)(\kappa_d + \delta) + r_f + \tilde{r}_i^F)$, where $\tilde{r}_i^F = f'(K_i^F)$, $K_{df}^F = K_i^F = Q_c^F + Q_d^F$, and $q_{cf}^{hF} = q_{df}^{hF} = K_{cf}^F = 0$. The trade flow in state h is from Clean to Dirty $x^h = Q_d^F$.*

Proposition 1 follows from Lemma 1 and Lemma 2 (proof in Appendix A.3).

Proposition 1. *For the Clean-Dirty interconnection, in the first-best, comparing free trade to autarky,*

i *all thermal production and capacity shift to the Dirty country;*

ii *$\exists\ \hat{\delta} \in (\bar{\delta}^A, \bar{\delta}^F)$, such that renewable capacity decreases if $\delta < \hat{\delta}$, and increases if $\delta > \hat{\delta}$;*

iii *the consumption level weakly increases in the Dirty country; $\exists\ \mathring{\delta} > \hat{\delta}$, such that consumption in the Clean country increases if $\delta < \mathring{\delta}$, and decreases if $\delta > \mathring{\delta}$;*

iv *$\exists\ \tilde{\delta} \in (\hat{\delta}, \bar{\delta}^F)$, such that carbon emissions increase if $\delta < \tilde{\delta}$, and decrease if $\delta > \tilde{\delta}$.*

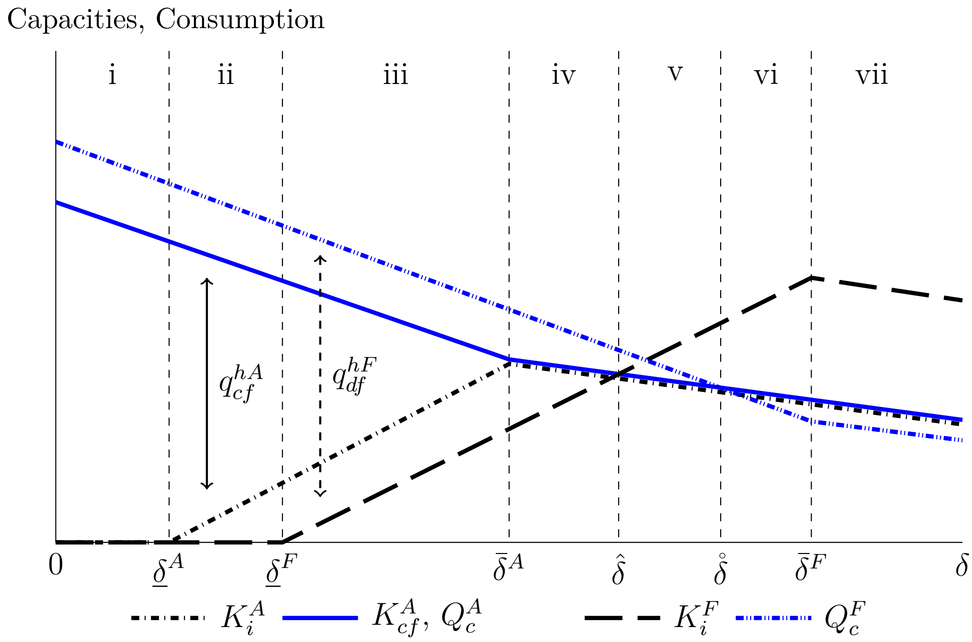
Optimal consumption and capacities

Proposition 1.i describes the concentration of thermal power in the Dirty country. This result is driven by the cost advantage of thermal production in the Dirty country. Because the marginal cost of thermal production is constant, efficiency requires that the Dirty country specializes in thermal power, and the Clean country holds no thermal capacity. This result need not hold if the marginal cost is convex.[15] However, it is still safe to conclude that thermal power is more concentrated in the Dirty country under free trade than under autarky (Figure 6b).

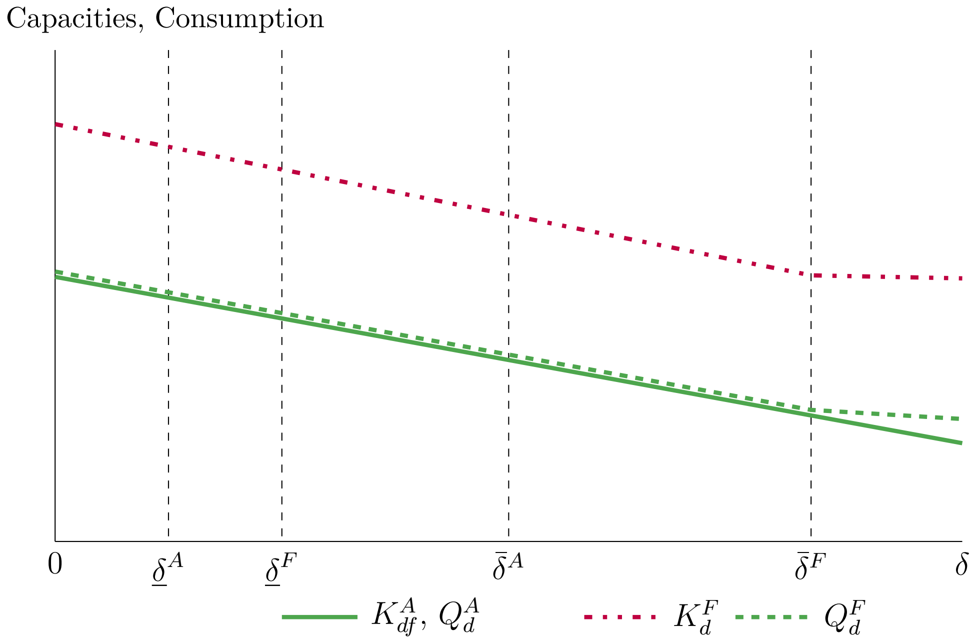
Proposition 1.ii implies that the renewable capacity under free trade can be lower or higher than autarky, depending on the SCC. Figure 6a illustrates this result. In case *ii*, where the Clean country builds renewable capacity under autarky, there is zero renewable under free trade. This is because when the transmission constraint is not binding, the two countries can be considered as one open market. Thus, the renewable capacity is installed if and only if its long run marginal capacity cost is lower than the Dirty country's marginal thermal production cost. In other words, opening to trade increases the SCC threshold for installing renewable capacity. In cases *iii* and *iv*, although there is some renewable

[15] If the marginal cost of thermal production is convex, depending on the respective cost functions in the two countries, the Clean country may have some or no thermal capacity. Since a convex marginal cost adds another layer of complexity and brings little additional insight, I abstract from the cost convexity.

Figure 6: Optimal capacities and consumption under autarky and free trade



(a) Clean



(b) Dirty

capacity under free trade, it is strictly lower than that under autarky. It follows that the marginal cost of the last unit of renewable capacity under autarky is strictly higher than that under free trade ($\tilde{r}_i^A = \nu(\kappa_c + \delta) > \nu(\kappa_d + \delta) = \tilde{r}_i^F$). On the other hand, with a high SCC, renewables can be installed to meet the consumption of both countries under free trade, whereas it is efficient to meet only the consumption of the Clean country under autarky. Therefore, free trade at high SCC facilitates the diffusion of renewables. The policy implication is that expanding interconnection does not necessarily leads to more renewables at the optimum.

Figure 6a and 6b also exhibit the optimal consumption levels in the Clean and Dirty country respectively. The Dirty country has a higher consumption level under free trade if and only if $\delta > \bar{\delta}^F$. In other words, when their demand in state h is fully met by imported renewables, the slope of their optimal consumption is smaller than under autarky. The situation for the Clean country is more complex. At a low SCC, the Clean country has a strictly higher consumption level under trade, because of the lowered cost in state l from importing. At a higher SCC, the Clean country may have a lower consumption given trade because of the increased investment in renewables. Since the cost of renewable capacity is increasing and convex, the excess capacity for export drives up the marginal cost. When the increase in the cost of renewables outweighs the decrease in that of thermal power, the optimal consumption may decrease compared to autarky.

Retail and wholesale prices

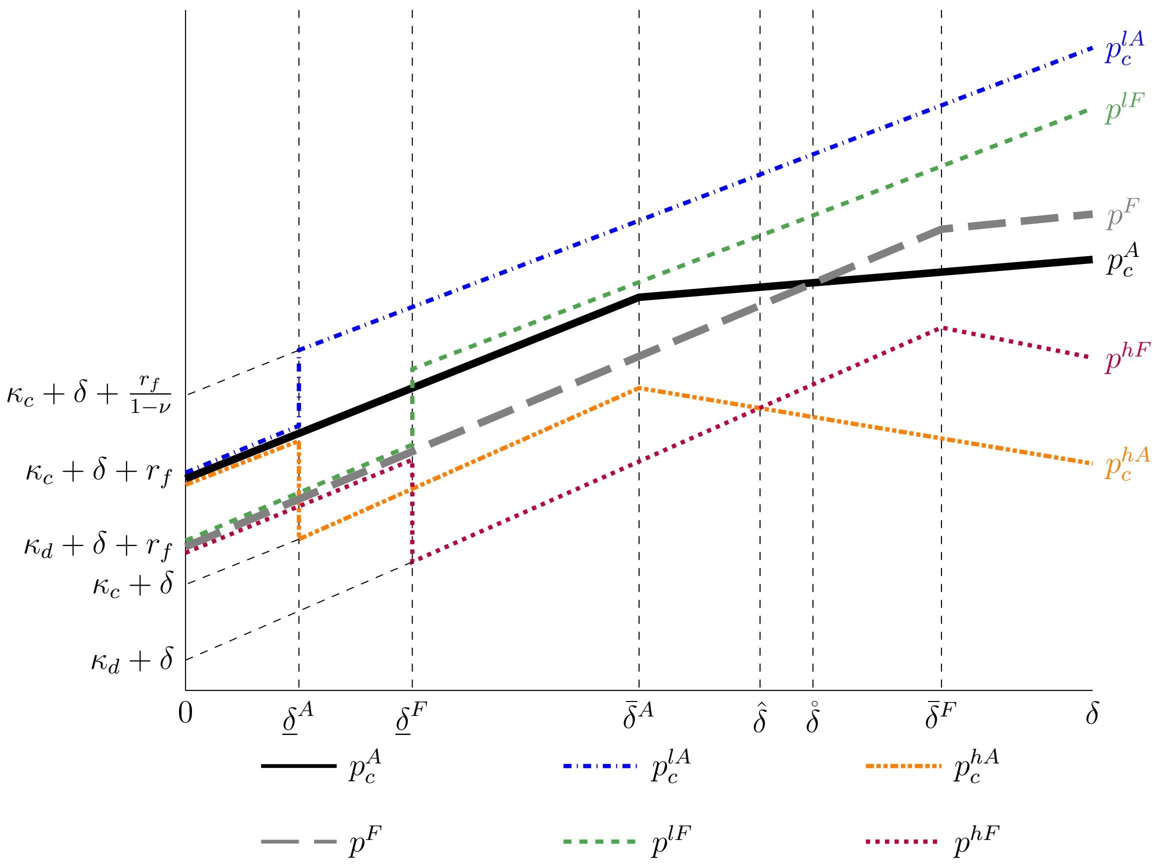
A global Pigouvian carbon tax can decentralize the optimal investment and consumption levels as a competitive market equilibrium. Under free trade, the absence of network congestion equalizes both the wholesale and retail prices in the two markets. Similar to the autarky case, the retail price equals the expected wholesale price in each state. The wholesale prices reflect the long-run marginal cost of the peak-load technology in the respective states (renewables in the state h and thermal in the state l). plus the marginal fuel cost and social damage from carbon emissions.

Figure 7 compares the free trade and autarky retail and wholesale prices. It is straightforward that in both cases, the wholesale price in state l is monotonically increasing in the SCC and is lower under free trade. The wholesale prices in state h first increase in the SCC, as more renewable capacities are installed, and then decreases as consumptions decrease and lower renewable capacity is needed. Moreover, the prices are not always lower under free trade than under autarky. At the threshold $\hat{\delta}$, their wholesale prices and renewable capacities are equal. Since the retail price is a linear combination of the wholesale prices, depending on the probabilities of the states, the free trade price may be lower or higher than that under autarky. The inverse relationship is reflected in the consumption levels.

On carbon emissions

The effect of free trade on carbon emissions is decomposed into the scale and technique effects (Antweiler et al. 2001). The scale effect refers to the increase in the consumption level in the relevant jurisdiction. The technique effect refers to the change in aggregate pollution arising from a switch to less pollution-intensive production technology. Net

Figure 7: The retail and wholesale prices under free trade and autarky

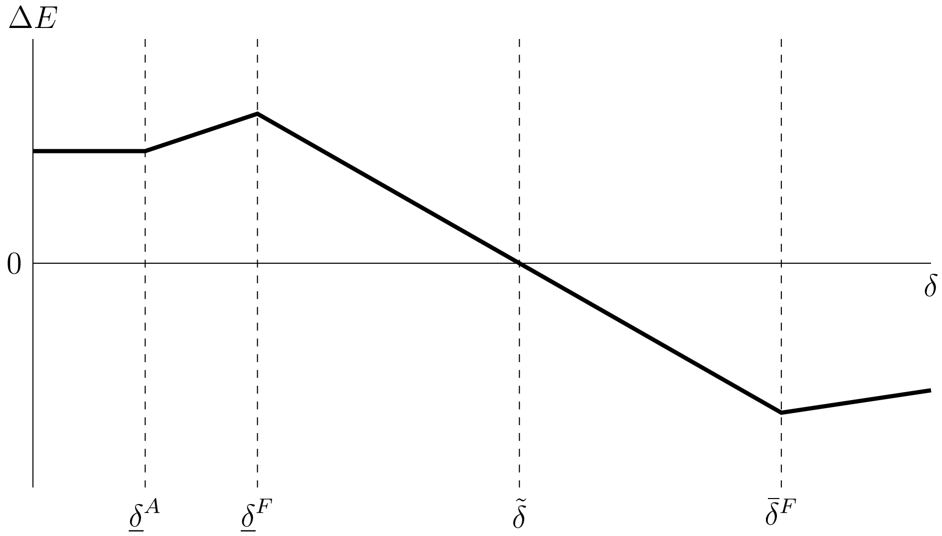


emissions are denoted as $\Delta E = E_F - E_A$, where $E^A = \sum_{j,s} q_{jf}^{sA}$ to $E^F = \sum_{j,s} q_{jf}^{sF}$. The net emissions change depending on the SCC, as shown below:

$$\Delta E = \begin{cases} \underbrace{Q_c^F - Q_c^A}_{\text{scale } +} > 0 & \text{if} \quad \delta \leq \underline{\delta}^A \\ \underbrace{Q_c^F - Q_c^A}_{\text{scale } +} + \underbrace{\nu K_i^A}_{\text{technique } +} > 0 & \text{if} \quad \underline{\delta}^A < \delta \leq \underline{\delta}^F \\ \underbrace{Q_c^F - Q_c^A}_{\text{scale } +} - \underbrace{\nu(K_i^F - K_i^A)}_{\text{technique } + -} \geq 0 & \text{if} \quad \underline{\delta}^F < \delta \leq \tilde{\delta} \\ \underbrace{Q_D^F - Q_D^A + Q_c^F - Q_c^A}_{\text{scale } + -} - \underbrace{\nu(K_i^F - K_i^A)}_{\text{technique -}} < 0 & \text{if} \quad \delta \geq \tilde{\delta} \end{cases} \tag{4}$$

Opening to trade allows the Clean country to import cheaper thermal power from the Dirty country, which both increases electricity consumption and reduces the social value to build local renewable capacities. If the SCC is lower than $\tilde{\delta}$, carbon emissions under free trade increase compared to autarky, which is due to the scale effect and the (reverse) technique effect going in the same direction to increase carbon emissions. However, when the SCC is higher than $\tilde{\delta}$, the technique effect of increased renewables offsets the scale effect of increased consumption, which leads to an overall decrease in carbon emissions (Figure 8). Note that when $\delta > \bar{\delta}^F$, $\frac{\partial \Delta E}{\partial \delta} > 0$. This is because the aggregate consumption level decreases more slowly with respect to the SCC under free trade than under autarky. A very high SCC may exist such that net emission becomes positive.

Figure 8: Net carbon emissions when comparing free trade to autarky Note: $\Delta E = E^F - E^A$



Proposition 1 arises from the fact that interconnection helps the diffusion of both renewables and thermal power. Depending on the SCC, either renewables or thermal power is more cost-efficient in generating electricity. Although expanding interconnection can always increase market efficiency, regarding deepening the penetration of renewables and reducing carbon emissions, the result is mixed.[16]

4.2 The Clean-Clean interconnection

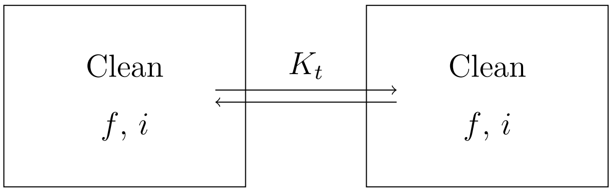
Now let us consider interconnecting two Clean countries that are symmetric except for the occurrence of the high and low renewable states (Figure 9). The unique aspect of this case is the imperfect correlation of wind and solar generation. Therefore, interconnecting two Clean countries reduces the variability of renewables and has the potential to decrease carbon emissions.[17] In the case of France and Spain, both countries have solar and onshore wind generation. Annual production shows that in 2016 the correlations of their solar production was 0.88, which is higher than that of their wind production (0.38), while

[16]This result has the same flavor as Lazkano et al. (2017). They find that storage boosts innovation in both renewable and conventional electricity generation. This is because storage reduces not only the intermittency of renewables, but also the ramping cost of conventional power plants.

[17] MacDonald et al. (2016) simulated an 80% reduction of CO_2 compared to the 1990 level for a US market connected by high-voltage direct-current transmission with high wind and solar deployment.

the cross-correlations of solar and wind production is negative (-0.13). This observation justifies the consideration of correlated states of nature, instead of simply regarding them as independent.

Figure 9: Illustration of electricity interconnection between two clean countries



Let us recall that the two countries jointly have four states of nature: (h, h), (h, l), (l, h), and (l, l), with probabilities $\sigma_{hh} = \nu^2 + \rho\nu(1-\nu)$, $\sigma_{hl} = \sigma_{lh} = \nu - \sigma_{hh}$, $\sigma_{ll} = 1 - \nu - \sigma_{hl}$ respectively. The generation possibilities in the corresponding states are

	Clean	Clean
h, h	K_i, q_f^{hh}	K_i, q_f^{hh}
h, l	K_i, q_f^{hl}	q_f^{lh}
l, h	q_f^{lh}	K_i,q_f^{lh}
l, l	K_f	K_f

Note that given the symmetric-countries assumption, trade is fully reciprocal and occurs only if one country is in the high renewables state (l, h). I assume that free disposal of renewable energy (i.e. curtailment) is allowed if the total capacity exceeds total demand.

$$\begin{aligned}
\max_{\substack{Q_c, q_f^s, K_i, x \\ s\in\{a,b,c\}}} \quad & 2W(Q_c, q_f^s, K_f, K_i, x; \kappa_c, \nu, \rho) \\
\text{s.t.} \quad & q_f^a + K_i \geq Q_c \\
& q_f^b + x = Q_c \\
& q_f^c + K_i - x = Q_c \\
& 0 \leq q_f^s \leq Q_c \qquad \forall s \in \{a, b, c\} \\
& K_i \geq 0 \\
& 0 \leq x \leq \min\{K_t, Q_c\}
\end{aligned} \tag{5}$$

In the Appendix A.4 I derive the following lemma:

Lemma 3. *The optimal installed capacities, production and electricity consumption in the two Clean countries for any given $K_t > 0$ (super-scripted T) are* *i* *If $\delta \leq \underline{\delta}^A$, there is no renewable capacity in either country and trade will not occur. $q_f^{sT} = Q_c^T = K_f^T = D(\kappa_c + \delta + r_f)$ ($s \in \{a, b, c\}$), $K_i^T = 0$ and $x^T = 0$. $\underline{\delta}^A = \frac{r_i}{\nu} - \kappa_c$.*

ii *If $\underline{\delta}^A < \delta \leq \bar{\delta}^A$, the renewable capacity can only satisfy partial local demand and trade will not occur. $Q_c^T = K_f^T = D(\kappa_c + \delta + r_f)$, $q_f^{sT} = Q_c^T - K_i^T$, $K_i^T = f'^{-1}(\nu(\kappa_c + \delta))$, and $x^T = 0$. $\bar{\delta}^A$ solves $f'^{-1}(\nu(\kappa_c + \bar{\delta}^A)) = D(\kappa_c + \bar{\delta}^A + r_f)$.*

iii *If $\bar{\delta}^A < \delta < \bar{\delta}^T$, the renewable capacity is equal to full local demand with excess supply for export, but is lower than the transmission capacity. $Q_c^T = K_f^T = D(\kappa_c + \delta + r_f)$, $q_f^{sT} = 0$, $K_i^T = f'^{-1}(\nu(\kappa_c + \delta))$, and $x^T = K_i^T - Q_c^T$. Renewable curtailment occurs in state (h, h) and equals x^T. $\bar{\delta}^T$ solves $f'^{-1}(\nu(c + \bar{\delta}^T)) = D(c + \bar{\delta}^T + r_f) + K_t$ and $\frac{\partial \bar{\delta}^T}{\partial K_t} \geq 0$.*

iv *If $\delta > \bar{\delta}^T$, renewable capacity is equal to full local demand plus the transmission capacity.*

$$\begin{cases} Q_c^T = K_f^T = D((1-\nu)(\kappa_c + \delta) + r_f + \tilde{r}_i^T) & \text{if } K_t < Q_c^T \\ Q_c^F = K_f^F = D(\sigma_{ll}(\kappa_c + \delta) + r_f + 2\tilde{r}_i^F) & \text{if } K_t \geq Q_c^T \end{cases}$$

$q_f^{sT} = 0$, $K_i^T = Q_c^T + x^T$, $\tilde{r}_i^T = f'(K_i^T)$, $\tilde{r}_i^F = f'(2Q_c^F)$ and $x^T = \max\{K_t, Q_c^T\}$. Renewable curtailment in state (h, h) equals K_t.

Proposition 2 follows from Lemma 1 and Lemma 3 (proof in Appendix A.5).

Proposition 2. *For the Clean-Clean interconnection of two symmetric countries, in the first-best, $\forall\ K_t > 0$, if $\delta < \bar{\delta}^A$ trade is equivalent to autarky; if $\delta > \bar{\delta}^A$, trade increases renewable capacity, and decreases consumption and carbon emissions.*

Proposition 2 is illustrated in Figure 10 with a comparison to the autarky case. It is intuitive that renewable capacity increases with trade with a high SCC. Since the two countries have not perfectly correlated renewable production, trade allows the countries to export renewables in the (h, l) and (l, h) states. Therefore, countries invest in more renewable capacity. But the excess capacity on top of their local demand is curtailed in state (h, h).

The increased renewable capacity under trade leads to the second part of Proposition 2, that for $\delta > \hat{\delta}$, interconnection decreases the optimal level of electricity consumption. This counter-intuitive result is driven by the convex cost of renewable capacity. I turn to the equilibrium wholesale prices to show the intuitions. Under constrained trade, the equilibrium wholesale price in each state for the two countries are as shown below.

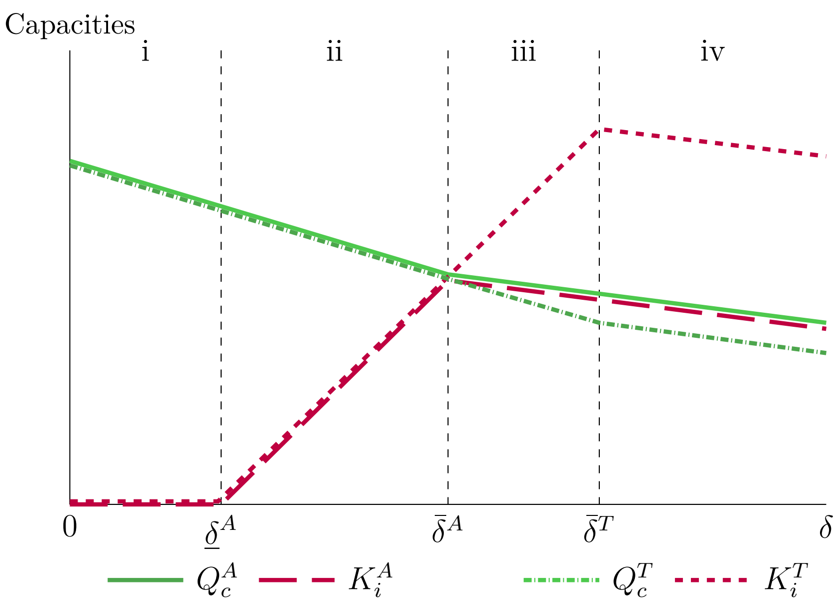
	Clean	Clean
p^{hh}	0	0
p^{hl}	$\frac{\tilde{r}_i^T}{\sigma_{hl}}$	$\kappa_c + \delta$
p^{lh}	$\kappa_c + \delta$	$\frac{\tilde{r}_i^T}{\sigma_{lh}}$
p^{ll}	$\kappa_c + \delta + \frac{r_f}{\sigma_{ll}}$	$\kappa_c + \delta + \frac{r_f}{\sigma_{ll}}$

The expected retail price given the equilibrium wholesale prices is thus

$$\begin{aligned} p^T =& \sigma_{hh} * 0 + \sigma_{hl}\frac{\tilde{r}_i^T}{\sigma_{hl}} + \sigma_{lh}(\kappa_c + \delta) + \sigma_{ll}\frac{r_f}{\sigma_{ll}} \\ =& (1-\nu)(\kappa_c + \delta) + r_f + \tilde{r}_i^T \end{aligned} \tag{6}$$

Compared to the autarky retail price for the Clean type, $p^A = (1-\nu)(\kappa_c + \delta) + r_f + \tilde{r}_i^A$, the only difference is the marginal cost of renewables. Therefore, all other things being equal, higher renewable capacity under trade leads to a higher retail price, and hence lower consumption level. This result holds true under free trade.

Figure 10: Optimal capacities and consumption for the Clean-Clean interconnection



Proposition 2 shows that expanding interconnection decreases carbon emissions only when coupled with high SCC. This is due to both the scale and technique effects of trade. For a low SCC, the scale and technique effects are both zero, as consumption levels and renewable capacity are not affected by an increase in transmission capacity. For a high SCC, with increasing K_t, more renewable capacity can be installed and exported in state (h, l), which also decreases the consumption level given the convex cost of renewables.

Therefore, the scale and technique effects go in the same direction to reduce carbon emission.

This following corollary regarding carbon emissions can be obtained (proof in Appendix A.6).

Corollary 1. *For a given level of SCC and transmission capacity, carbon emissions weakly increase (resp. decrease) with more positively (resp. negatively) correlated intermittency.*

Corollary 1 suggests that the reduction in carbon emissions is more pronounced if the two interconnecting countries have more negatively correlated renewable production, e.g., interconnecting one country with solar PV and one country with wind. The intuition is straightforward: more negatively correlated intermittency increases the probability of only one country with renewable production, which decreases the curtailment rate of renewable power and reduces output from thermal power.

Note that Proposition 2 and Corollary 1 are true if and only if free disposal of renewables is allowed. When curtailment is not allowed, e.g. a policy that forces all renewable production to be taken by the grid, then for grid safety concerns, renewable capacity is capped by the local demand. Therefore, it is inefficient to have a renewable capacity larger than the consumption level of one country. In this symmetric case, there will be no trade in any state and there can be no gains from interconnection. Not allowing for curtailment completely undermines the insurance motive of interconnection, and results in a lower social welfare level.

There are many empirical observations of renewable curtailment in the real electricity markets (Bird et al. 2016). They are of great concerns as they potentially reflect market inefficiency, overcapacity, strategic firm behavior, or inefficient policy designs.[18] Although curtailment may be inefficient under low shares of renewable power, the results in this section show that with high share of renewable capacity, curtailment can be efficient to achieve higher renewable penetration and carbon reduction. Naturally, curtailment could be avoided if more countries are interconnected, especially to countries without renewables, or through the deployment of grid-scale storage facilities (Loisel et al. 2010).

[18] This concern is addressed by an extensive literature. For example, Fabra and Llobet (2019), Golden and Paulos (2015), Kakhbod et al. (2019), and Luo et al. (2016).

5 Calibrated Simulation

In this section, I calibrate the model using country-level electricity market data. I then simulate the long-run equilibrium electricity consumption, wholesale prices, renewable capacity, and carbon emissions for given levels of interconnection capacity and SCC. Furthermore, I conduct a benefit-cost analysis, comparing the simulated gains from additional transmission capacity with the investment cost of transmission lines.

5.1 Data source and calibration methodology

In the simulation, I relax the model assumption of symmetric demand and uniform capacity cost for the interconnected countries and construct country-specific parameter values. To estimate the parameters, I obtain data for the year 2016 from a variety of sources specified below for two pairs of countries: Germany (DE) and Poland (PL), France (FR) and Spain (ES).

The DE-PL interconnection represents the Clean-Dirty case. In 2016, 89% of Poland's total electricity generation came from fossil fuel sources while Germany had a mix of nuclear (14.9%), fossil (42.2%) and a substantial amount of intermittent renewables (20.5%). Germany is also in the process of phasing out nuclear power and coal for generating electricity. Therefore, by looking at the interconnection of these two countries it is possible to draw implications on how interconnection can facilitate or impede achieving these policy targets, and also provide inferences on interconnection between other countries/regions with similar energy profiles (e.g., China-Japan, California-Arizona).

The interconnection between France and Spain (FR-ES) represents the Clean-Clean case. Electricity in France is predominantly generated by nuclear power plants (72.5%), with the residual supply mainly from gas (6.8%) and intermittent renewables (5.2%). Spain has a balanced mix of nuclear (22.5%), thermal (33.3%), and renewable (24%) power. Although France and Spain are geographically close, their wind and solar generation are imperfectly correlated. Their annual wind-wind, solar-solar, and wind-solar production correlations are respectively 0.38, 0.88, and -0.13. Therefore, I am able to explore the effect of the correlation coefficient on carbon emissions.

Demand side calibration

On the demand side, I calibrate the gross surplus function of electricity consumption. I take an isoelastic demand function in the form $D_j(p_j) = Z_j p_j^{\varepsilon_j}$, where p_j is the state-independent equilibrium retail price, $\bar{p}_j$ is the value of lost load (VoLL), ε_j is the long-run price elasticity of electricity demand, and Z_j is the demand parameter in country j ($j \in$ DE, PL, FR, ES).[19]

The literature provides a wide range of elasticity estimates (from -0.1 to 1.8), depending on the country, year, and sectors estimated.[20] Therefore, I follow the similar strategy used in Reguant (2019) to calibrate the long-run elasticity term. I take a benchmark elasticity for the household and non-household sector, and form a country-level elasticity by taking the weighted average of the elasticity. The sector weights, which are defined by the share of final electricity consumption by each sector, are obtained from the European Environmental Agency (EEA) (Table 1).

Table 1: Demand elasticities and shares by customer class

Sector	Elasticity	Share			
		FR	ES	PL	DE
Household	-0.5	36%	30%	22%	25%
Non-household	-1	64%	70%	78%	75%

The demand parameter Z_j is calibrated using the 2016 retail price and consumption data obtained from EuroStat and ENTSO-E respectively, using the following formula:

$$Z_j = q_{j0} * p_{j0}^{-\varepsilon_j} \tag{7}$$

where q_{j0} is the average hourly consumption for country j and p_{j0} is the sector weighted retail price of electricity (including all taxes and levies, shown in Table 2). The sector weights are the same as in Table 1.

Table 2: Sector specific electricity retail prices

Sector	Unit	Annual average retail price			
		FR	ES	PL	DE
Household	€/MWh	169.8	223.5	134.2	297.3
Non-household	€/MWh	111	129.1	99.8	196.6

The VoLL for each country is taken from a report from the Agency for the Cooperation of Energy Regulators (ACER) report (ACER 2018). Table 3 exhibits the calibrated values.

Supply side calibration

[19] The VoLL can be interpreted as the maximum price that consumers are willing to pay to be supplied with energy. This can be regarded as an upper bound for the retail price. The reason to impose an upper bound for is to have a non-infinite consumer surplus.

[20] For example Auray et al. (2018) estimate the long-run elasticity for the residential sector in France ranging from -1.4 to -1.8. Chang et al. (2019) estimate the elasticity for the industrial sector for OECD countries ranging from -0.1 to -0.5. Burke and Abayasekara (2018) estimate the long-run residential and industrial elasticity to be -1.16 and -1.34 respectively in the United States.

Table 3: Demand side calibrated parameter values for each country

Variable	Definition	Source	Unit	FR	ES	PL	DE
ε_j	Demand elasticity	Literature		-0.82	-0.85	-0.89	-0.88
$\bar{p}_j$	Value of lost load	ACER report	€	6920	7880	6260	12410
p_{j0}	Sector weighted retail price	EuroStat	€/MWh	132.2	157.4	107.3	221.5
q_{j0}	Annual average consumption	ENTSO-E	MWh	54392	28508	18714	54768

On the supply side, I aggregate the electricity generation profile of each country into three types: nuclear, thermal, and renewables. Nuclear is considered as the baseload technology (subscripted b) in France, Spain, and Germany, which is assumed to run at all states due to its inflexibility. Thermal power, including gas, coal, and oil (subscripted f), has state dependent output. Of the renewables (subscripted i), I consider both wind and solar power, generating output at full capacity in the renewable state.

Baseload and thermal technology For each fuel type (denoted by m, $m \in \{coal, gas, oil\}$) in the thermal power, the country specific marginal capacity costs (r_{jfm}) and fuel and operation costs (c_{jfm}) are obtained from the IEA (2015) report.[21] I then compute the capacity and production weight for each fuel type using data from ENTSO-E. Thus, the thermal power marginal costs for each country (c_{jf}, r_{jf}) are the weighted average of the marginal costs of each fuel type:

$$c_{jf} = \sum_m \frac{q_{jfm}}{Q_{jf}} * c_{jfm} \tag{8}$$

$$r_{jf} = \sum_m \frac{k_{jfm}}{K_{jf}} * r_{jfm} \tag{9}$$

q_{jfm} is the annual output of technology m in country j, Q_{jf} is the total annual output of thermal power, k_{jfm} is the installed capacity of technology m in country j, and K_{jf} is the total capacity of thermal power.

For nuclear power, the marginal fuel costs (c_{jb}) and marginal capacity costs (r_{jb}) are taken directly from the IEA (2015) report. The capacity for the baseload technology (K_{jb}) is capped at the current level, obtained from ENTSO-E. This assumption allows for the fade-out and not the expansion of nuclear.

Intermittent renewables I calibrate the marginal capacity cost function of wind and solar using data from the Global Wind Atlas and Solargis respectively (see Appendix A.7 for detailed methodology). The convex cost functions capture the heterogeneity in actual power yield. The capacity factors ν_j and correlation coefficient ρ are calculated using the

[21] The IEA (2015) report project costs for the near future (5 years). So here I assume that the projected cost in 2015 is applicable in 2016.

actual generation data from ENTSO-E.[22] The upper bound for wind capacity ($\bar{K}_{j,wind}$) is taken from a European Commission report (Dalla Longa et al. 2018). The upper bound for solar capacity in Spain is approximated using the following formula (see Appendix A.7 for land area calculation):

$$\bar{K}_{j,solar} = \frac{\text{Land area avaliable for solar panels (km}^2\text{)}}{\text{per MW solar panel surface area (km}^2\text{/MW)}} \tag{10}$$

Emissions factor The electricity producers' cost of emissions for each unit of electricity produced depends on the carbon emission intensity of the fuel source. According to a report from the the Intergovernmental Panel on Climate Change (IPCC), generating 1 kWh from coal can emit 670-870 gCO_2eq, while gas power plants emit 350-490 gCO_2eq/kWh (Schlömer et al. 2014). The country-level emission factors vary as a function of the composition of production in each country. I construct country-level emission factors (e_j) for the thermal technology and use them to calculate the actual carbon price per MWh of electricity output. I assume that the technology for each fuel type is identical across countries. I take the median life-cycle emissions factor reported in Schlömer et al. (2014) for each fuel type.

Local electricity tax France, Spain, Germany, and Poland also have local electricity taxes on top of the marginal costs of electricity generation. The tax levels are obtained from the EuroStat retail prices data and denoted as τ_j. In the simulations, I assume that the local taxes are maintained at the current levels and are imposed on electricity generated from non-renewable sources.

Table 4 summarizes the calibrated parameter values used in the model simulation.

[22] The capacity factor $\nu_j = \frac{\text{actual annual generation MWh}}{\text{installed capacity MW * total hours of the year h}}$.

Table 4: Supply side calibrated parameter values for each country

Variable	Definition	Source	Unit	FR	ES	PL	DE
c_b	Baseload fuel cost	IEA report	€/MWh	7.00	7.00	-	7.00
r_b	Baseload capacity cost	IEA report	€/MWh	20.18	20.18	-	20.18
K_b	Baseload capacity	ENTSO-E	MW	63130	7572	-	10793
c_f	Thermal fuel cost	IEA report	€/MWh	46.41	40.67	18.13	17.39
r_f	Thermal capacity cost	IEA report	€/MWh	8.03	5.63	7.50	6.72
e_j	Emission factor	IPCC Annex III	tCO_2/MWh	0.55	0.64	0.81	0.80
τ_j	Sector weighted local electricity tax	EuroStat	€/MWh	48.9	33.6	24.7	127.7
$\bar{K}_{j,wind}$	Maximum wind capacity	JRC report	MW	731000	944000	-	308000
$\alpha_{j1,wind}$[a]	Parameters for wind cost	Global Wind Atlas		$3.36 * 10^{-3}$	$4.51 * 10^{-12}$	-	$5.99 * 10^{-9}$
$\alpha_{j2,wind}$	Parameters for wind cost			10.78	30.06	-	22.4439
$\alpha_{j3,wind}$	Parameters for wind cost			27.44	56.10	-	30.5000
$\alpha_{j4,wind}$	Parameters for wind cost			9.96	10.75	-	20.0850
$\nu_{j,wind}$	Average wind capacity factor	ENTSO-E		0.19	0.23	-	0.18
ρ_{wind}	Wind-wind correlation	ENTSO-E		0.37931		-	-
$\bar{K}_{j,solar}$	Maximum solar capacity	GeoNetwork	MW	-	1009003	-	-
$\alpha_{j1,solar}$[a]	Parameters for solar cost	Solargis		-	$7.63 * 10^{-6}$	-	-
$\alpha_{j2,solar}$	Parameters for solar cost			-	13.95	-	-
$\alpha_{j3,solar}$	Parameters for solar cost			-	2.68	-	-
$\alpha_{j4,solar}$	Parameters for solar cost			-	15.15	-	-
$\nu_{j,solar}$	Average solar capacity factor	ENTSO-E		-	0.20	-	-
ρ_{solar}	Wind-solar correlation	ENTSO-E		-0.1358		-	-

[a] Fitted renewable capacity cost function: $\alpha_1 e^{\alpha_2 x} + \alpha_3 x + \alpha_4$.
x in the function is the percentage of total available wind or solar capacity used. $x \in [0, 1]$.

5.2 Simulation results

I present simulations for the Germany-Poland (DE-PL) and France-Spain (FR-ES) interconnections. I assume exogenous variations in the transmission capacity and the SCC, and optimize over capacities, production, consumption, and trade. I also assume that the interconnection capacities in the rest of the interconnected region remain unchanged.

5.2.1 Germany and Poland

Social welfare and prices

Figure 11 shows the impact of expanding transmission from 0 gigawatt (GW) to 20 GW on social welfare, under SCC of €25, €55, €85, and €125 per metric ton of CO_2. We can see that the DE-PL interconnection is welfare-enhancing compared to the autarky case. Moreover, welfare increases at a faster rate for lower levels of SCC.

Figure 11: Simulated percentage change in social welfare with DE-PL interconnection

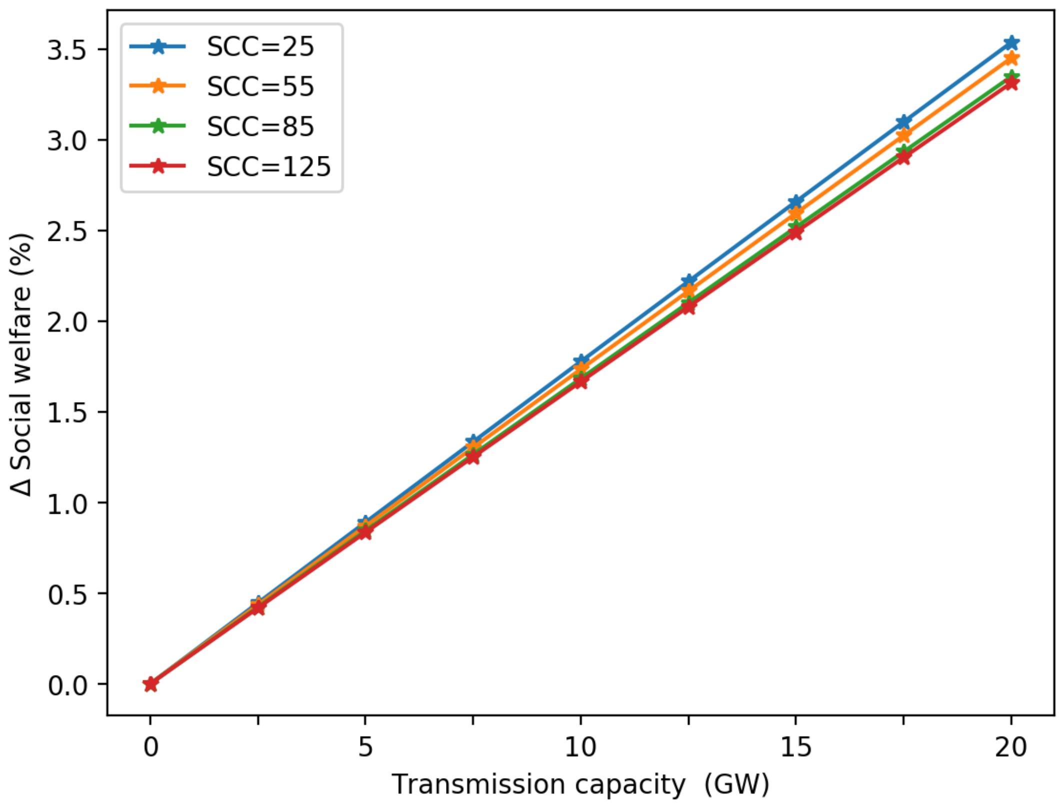


Figure 12 exhibits how retail prices in Germany (left) and Poland (right) countries change with respect to the transmission capacity and at different levels of SCC. We can see that at SCC equals to 25, 55, and 85 €/tCO_2 the retail prices in Germany decreases with more transmission capacity (i.e. consumption increaes). The retail prices in Poland remains unchanged. However, at SCC equals to125 €/tCO_2, retail price in Germany increases with more transmission capacity and decreases in Poland at high transmission capacities. we can see that the gains are shared unevenly between consumers and producers. This result is in line with Proposition 1.iii. Increased transmission does not necessarily lead to lower prices and higher consumption.

Figure 12: Simulated percentage change in retail prices in Germany and Poland

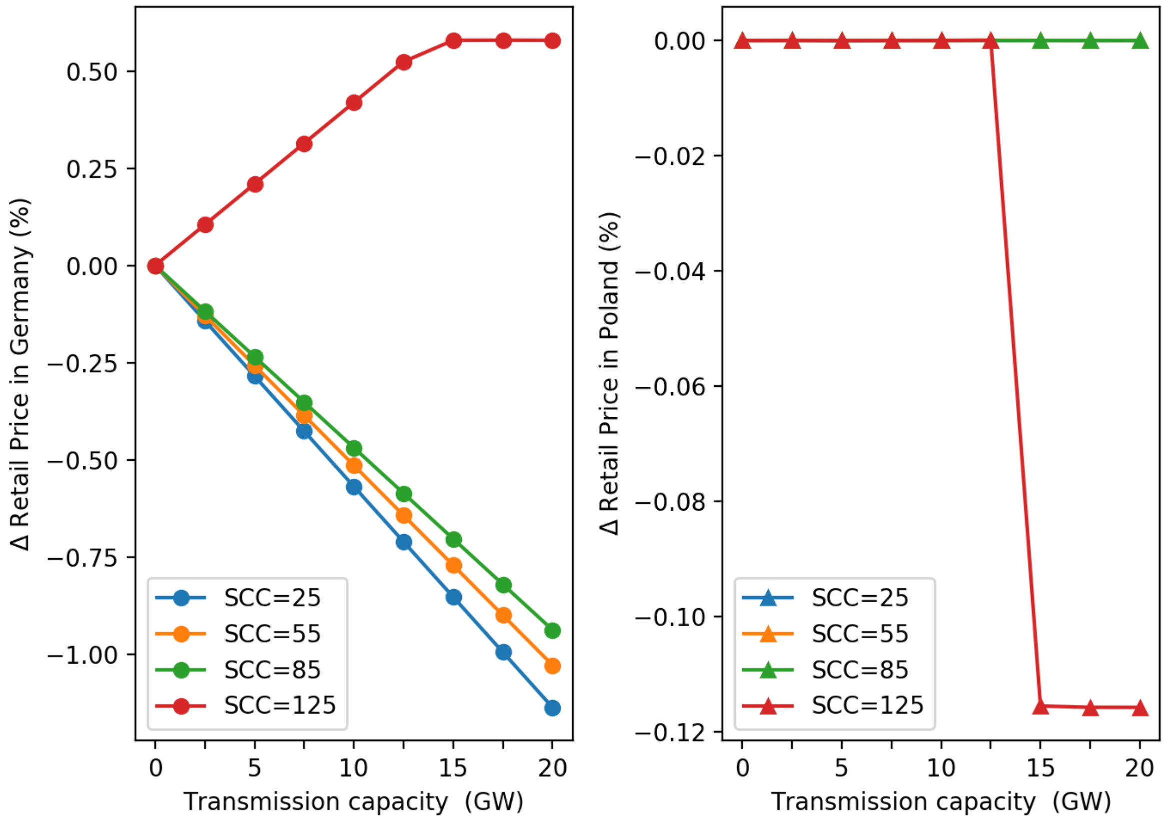
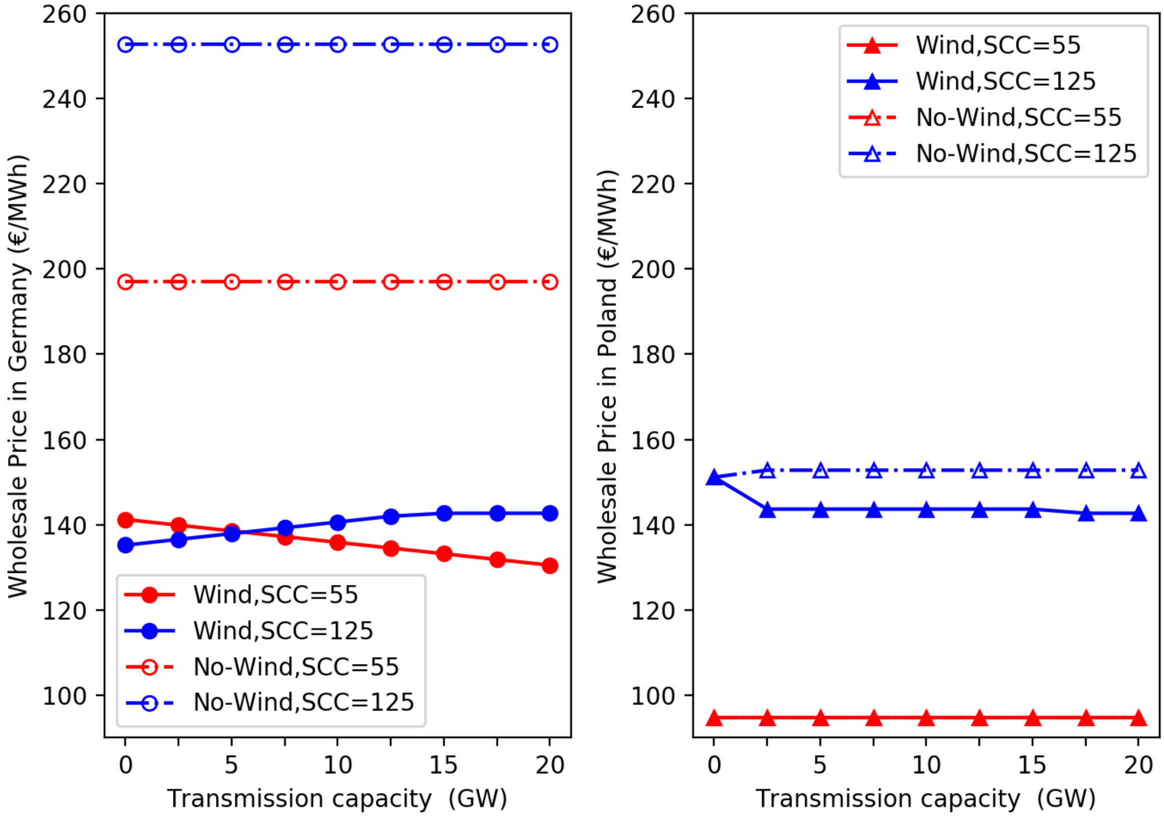


Figure 13 shows the state-dependent wholesale prices in Germany (left) and Poland (right) countries for SCC equals to 55 and 125 €/tCO_2. Clearly, in most cases, the wholesale price in Poland is lower than that in Germany. Therefore, Germany imports at maximum transmission capacity from Poland. The only exception is in the wind state with high SCC. In this case, the wholesale price in Germany is lower than that in Poland, Poland imports from Germany until the price difference diminishes (solid blue line at high transmission capacity).

Installed capacities and production

Figure 14 shows the respective capacity share of each fuel type in Poland (upper) and Germany (lower). It can be observed that the thermal capacity in Poland increases with more transmission capacity, and the reverse holds true for Germany. Therefore, thermal capacity shifts to Poland because of the cost advantage. The wind capacity in Germany

Figure 13: Simulated percentage change in retail prices in Germany and Poland



decreases with more transmission capacity. But under high transmission capacity, a higher SCC leads to more renewables.

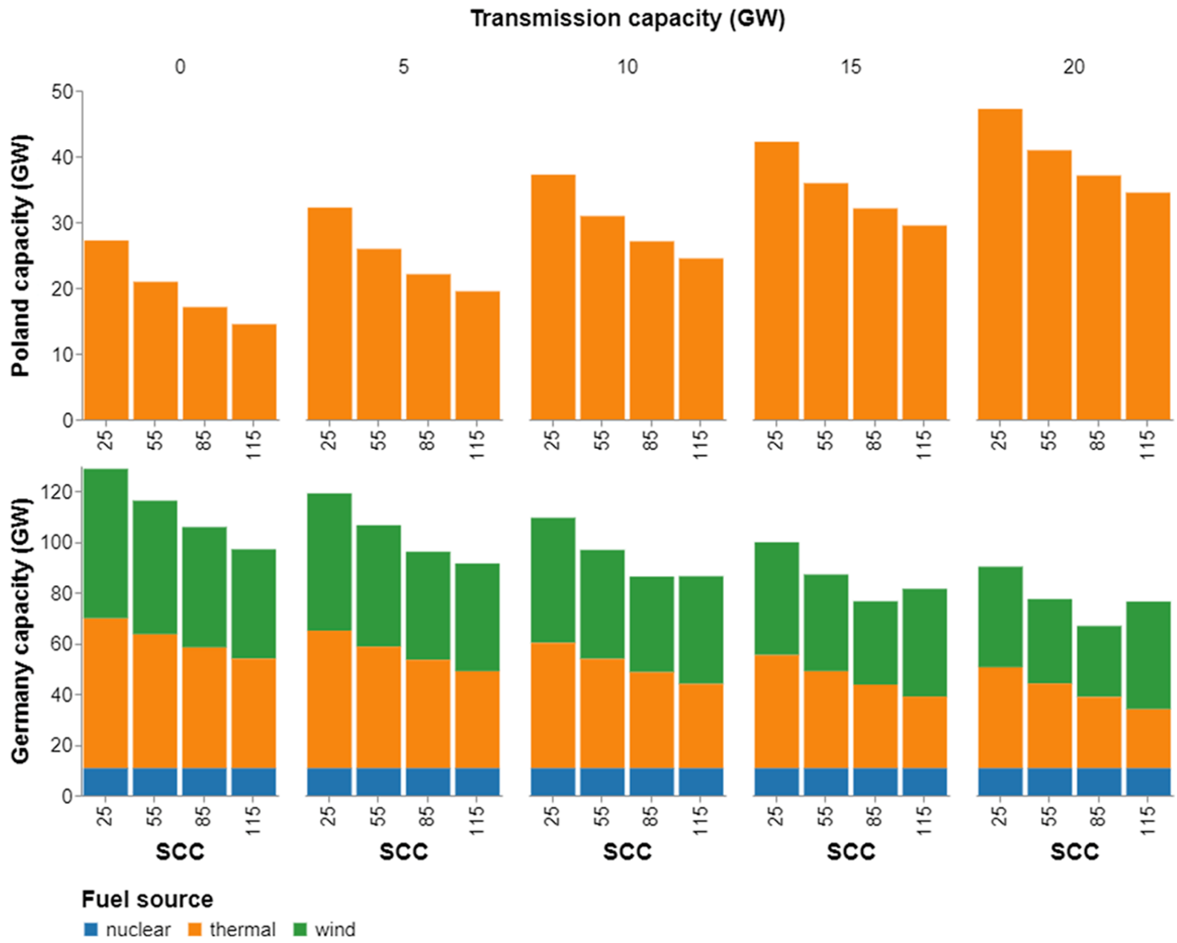
Moreover, the simulation shows that nuclear capacity is constant across all cases. This is because nuclear power emits little CO_2 so the SCC does not affect its marginal production cost. Therefore, if Germany were to phase-out all of its nuclear power, they need to substitute with more thermal power capacity (or increase transmission capacity to import from other countries).

Figure 15 exhibits the share of wind production for given transmission capacities with increasing SCC. It is clear from the figure that for any transmission capacity, there exists a threshold level of SCC such that renewable production share decreases if the SCC is lower than the threshold. This result is consistent with Proposition 1 ii. We can infer that at the current level of SCC (35 €/tCO_2), expanding interconnection between Germany and Poland may lead to a decreasing renewables as a share of final energy consumption.

Carbon emissions

Figure 16 shows the corresponding carbon emissions for different levels of SCC and transmission capacity. It is straightforward from the figure that at low levels of SCC (SCC

Figure 14: Simulated fuel type capacity with DE-PL interconnection



<110 €/tCO_2), increasing transmission capacity exacerbates total carbon emissions. The result is driven by the low electricity taxes in Poland. However, at high levels of SCC, interconnection facilitates the diffusion of renewables and reduces overall carbon emissions.

5.2.2 France and Spain

In the FR-ES case, the gains from interconnection vary depending on the correlation of renewables. I simulate two separate cases, FR wind-ES wind and FR wind-ES solar, to explore the effect of intermittency correlation. The simulation for FR-ES can shed light on how interconnection can facilitate the diffusion of renewable power with correlated production.

Renewable curtailment

The renewable curtailment rate is measured by the unused renewable production over

Figure 15: Simulated wind production with DE-PL interconnection

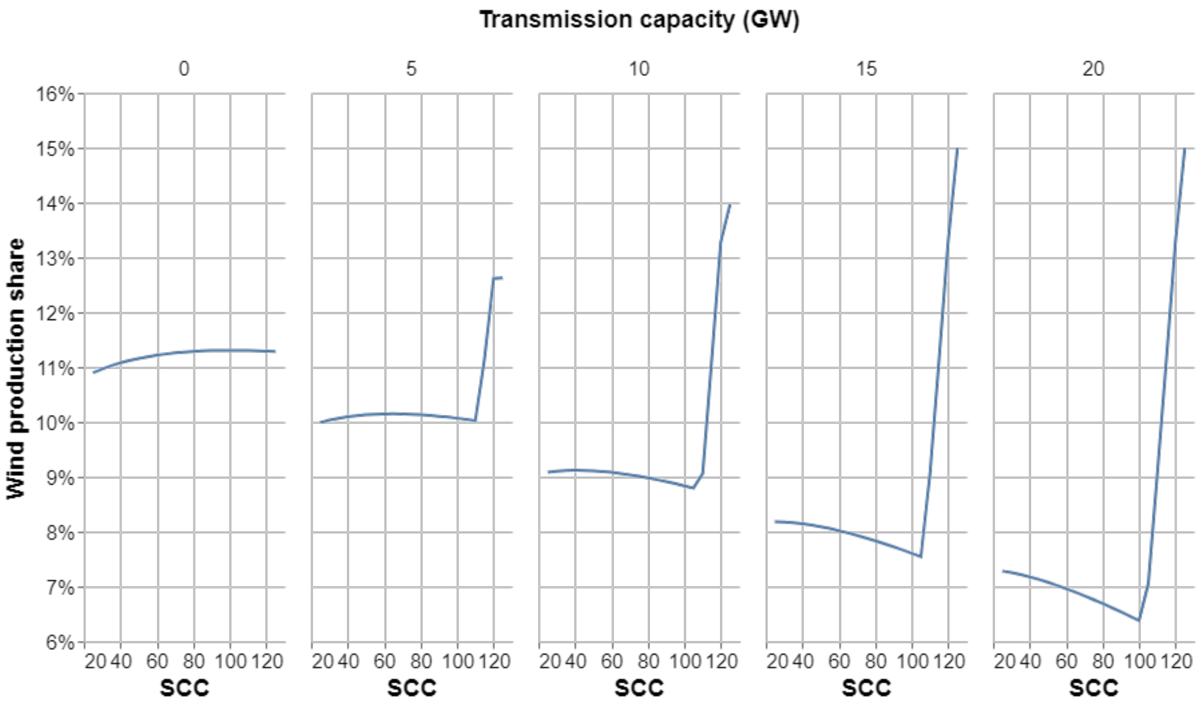
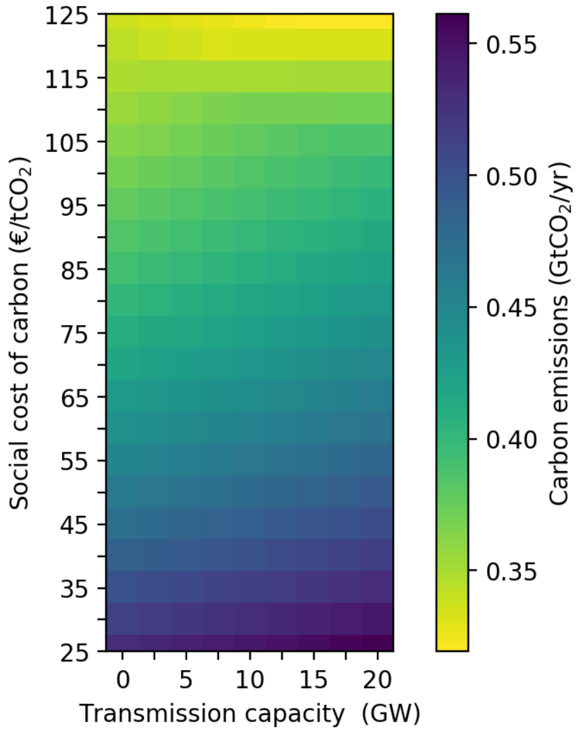


Figure 16: Simulated total emission with DE-PL interconnection

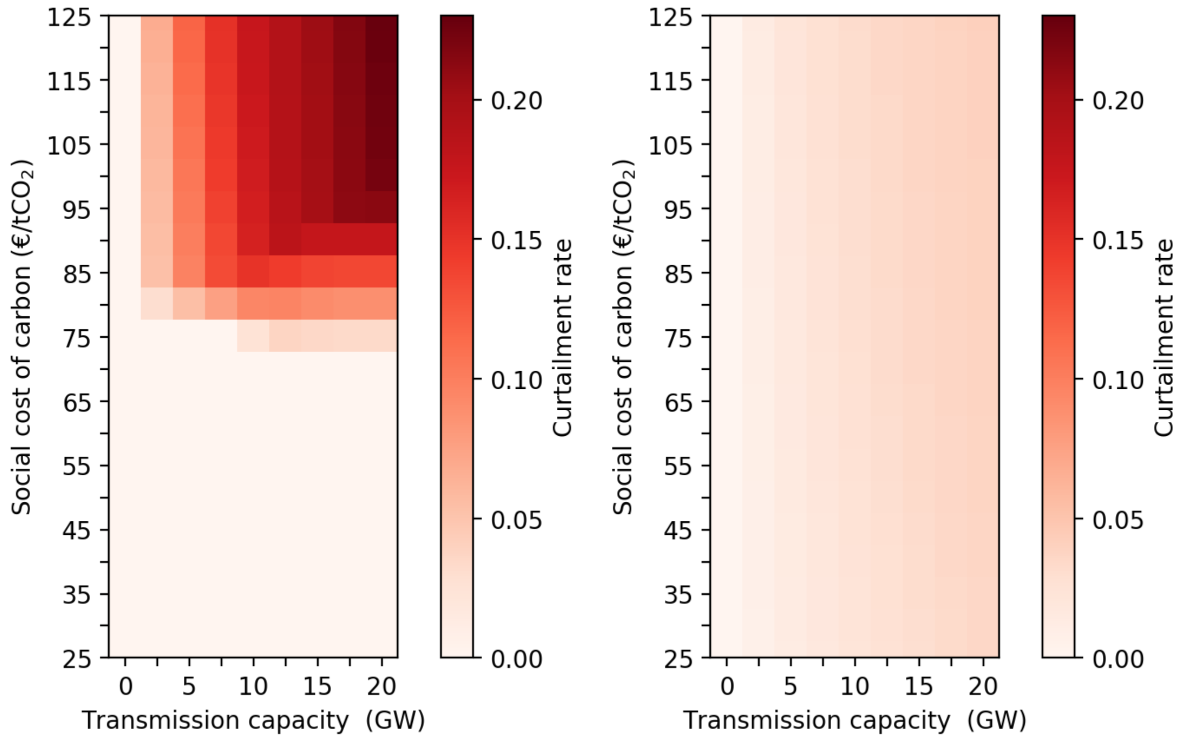


the total renewable output. The curtailment rate thus depends on two factors: the probability of both countries producing with renewable power simultaneously and the excess renewable capacity available for exportation.

Figure 17 shows how the renewable curtailment rate changes under increasing transmission capacity and for different levels of correlation coefficient. For 17a and 17b the curtailment rate is shown on the same scale. Thus, it is straightforward that at lower correlation coefficient (Figure 17b), the curtailment rate is much lower than at higher correlation coefficient (Figure 17a). Therefore, interconnecting two countries with more negatively correlated renewable production can make more efficient use of renewable capacities.

Moreover, the curtailment rate increases with higher SCC and higher transmission capacity. This is because both the SCC and transmission capacity motives the investment in renewable capacity. The higher the excess renewable capacity for exportation, the higher the curtailment rate. Thus, with the increasing share of renewables in the grid, curtailment can be efficient in some states of nature.

Figure 17: Simulated curtailment FR-ES interconnection



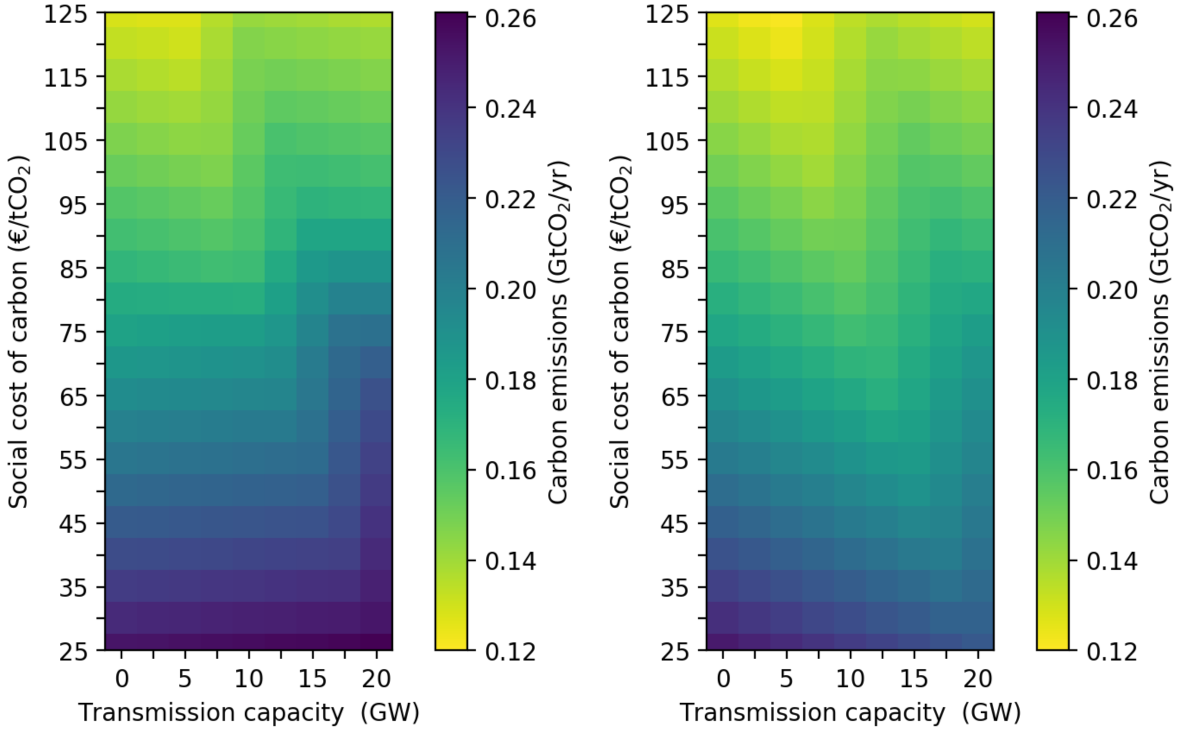
(a) FR Wind-ES Wind **(b)** FR Wind-ES Solar

Carbon emissions

In the case of FR wind-ES wind interconnection, expanding interconnection at low carbon prices increases carbon emissions. This result is driven by the scale effect of trade, where consumption levels increases with trade. However, at high carbon prices, thermal production becomes less competitive and more wind capacities are installed. Consequently, total emissions decrease.

Comparing 18a and 18b we can conclude that the total emissions in the FR wind-ES solar case is lower than that in the FR wind-ES wind case. This is consistent with Corollary 1. Because of the lower curtailment rate with more negatively correlated renewable energy across countries, over all carbon emission level is also lower.

Figure 18: Simulated carbon emission with FR-ES interconnection



(a) FR Wind-ES Wind **(b)** FR Wind-ES Solar

5.3 EU 2030

The existing interconnection capacity between DE-PL and FR-ES are 1700 MW and 2800 MW respectively. To achieve the EU 2030 interconnection target, DE-PL and FR-ES need to achieve 7000 MW and 13500 MW (TYNDP 2016).[23]

Table 5 exhibits the model simulated capacities, production, consumption, and emission levels change in response to achieving the EU 2030 interconnection target with respect to the status quo. The SCC is taken at the projected 2030 level of €45/tCO_2 (for a 3% discount rate).

For the DE-PL case, achieving the EU2030 target increases total consumption level and the thermal power capacity; and it reduces renewable capacity and the share of renewable production. Consequently, carbon emissions increase due to both the scale effect

[23] These interconnection targets are the upper bound of the target estimates.

Table 5: Simulated responses to the EU 2030 target

EU 2030	DE-PL	FR wind-ES wind	FR wind-ES solar
Transmission capacity	7 GW	13.5 GW	13.5 GW
Thermal capacity	0.21%	-0.11%	-0.35%
Renewable capacity	-9.68%	-0.11%	37.65%
Renewable production share	-9.85%	3.90%	34.59%
Consumption	0.18%	-0.05%	-0.18%
Carbon emissions	1.69%	1.74%	-7.18%

and the reverse technique effect of trade. This result is driven by the high electricity taxes in Germany. If the market become more integrated through expanded interconnection, Poland can bid at a much lower price for electricity production. Therefore, in equilibrium, Germany invest in less renewable capacity and shift thermal power production to Poland. This leads to lowered consumer prices and thus increased consumption and carbon emissions.

For the FR-ES case, the effect of the EU2030 target depend on the type of energy mix we consider in each country. If both countries have only wind energy, expanding interconnection decreases total consumption level, thermal and renewable capacities; and it increases carbon emissions. However, if France installs wind turbines and Spain installs solar panels, the negative correlation of the two energy sources leads to an overall increase in renewable capacity and thus lowered carbon emissions. Therefore, the effect of the EU2030 target in reality should be bounded by the FR wind-ES wind and FR wind-ES solar case.

The EU wide 2030 climate targets are set to decrease carbon emissions in the power sector by 43% (compared to the 2005 level) and increase the share of renewables in final energy consumption to 31%. The carbon emission goal can be translated into a decrease of 31% from the 2016 level.[24] Therefore, achieving the interconnection target can potentially contribute to -5 $\sim$ 23% of this goal. In addition, the 2030 EU climate and energy framework has set a binding renewable energy target to account for at least 32% of final energy consumption. Even in the FR wind-ES solar case, which has the highest renewable production share of 14%, we are still far from meeting the target.

[24] The total EU green house gas (GHG) emissions in 2005 was 5351 $MtCO_2e$ and in 2016 was 4441 $MtCO_2e$. Thus, the equivalent of 43% decreases compared to the 2005 level is 31% decrease compared to the 2016 level.

5.4 Benefit-cost analysis of electricity interconnection

In this part, I conduct a benefit-cost analysis (BCA) to look at whether the social welfare benefits can outweigh the high upfront investment cost of the transmission lines. I choose the benefit-cost ratio (BCR) as the evaluation criterion in this case. If BCR>1, then a project generates more benefit than cost. The BCR is calculated according to the following formula:

$$\text{BCR}(K_x) = \frac{\sum_{t=0}^{T} \frac{B_t(K_x)}{(1+r)^t}}{C(K_x)} \tag{11}$$

where B_t is the social welfare benefit generate in period t, C is the investment cost, K_x is the transmission capacity, T is the lifetime of the project, and r is the discount rate.

The cost of transmission varies significantly according to capacity, distance of transmission lines and the type of terrain (undersea, through mountains or overhead). For the DE-PL interconnectors, I take the median reported investment cost for 380/400 kV 2 circuit overhead alternating current (AC) transmission lines from ACER (2015). For the FR-ES interconnectors, I take a capacity weighted average cost of the existing or planned transmission lines.[25]

The investment cost for a given level of transmission capacity is calculated according to

$$C(K_x) = \frac{K_x * \bar{c}_{ij} * D_{ij}}{1 - \bar{l}_{ij}} \tag{12}$$

where D_{ij} is the length of the transmission lines between two nodes i and j $(i, j \in \{FR, ES, DE, PL\})$, $\bar{c}_{ij}$ is the average per kilometer Megawatt cost, and $\bar{l}_{ij}$ the average loss of electricity on the transmission lines. Table 6 presents the values taken for the BCA.

[25] Between France and Spain, there is an existing interconnection of 1400 MW that extends 65 km through the Pyrenees. The investment cost for this project was around 700 M€. Another recently permitted interconnection project is the Biscay Gulf Project, which will build a 2200 interconnection that extends for 370 km undersea. The estimated investment cost for this project is 1750 M€.

Table 6: Cost parameters of HVDC transmission lines

Interconnection	Unit	DE-PL	FR-ES
Average cost ($\bar{c}_{ij}$)	€/MW-km	1023	4305[a]
Average line loss ($\bar{l}_{ij}$)	/GW	0.88%	0.72%
Average distance (D_{ij})	km	170	251
Lifetime (T)	years	25	25
Interest rate (r)		4%	4%

[a] The large difference between the cost of DE-PL and FR-ES is mainly due to the terrine type.

The benefit for each period is the gain in social welfare with the transmission capacity.

$$B_t(K_x) = W_t(K_x, \delta_t) - W_t(0, \delta_t) \tag{13}$$

I take values suggested by the ENTSO-E's BCA guidelines for the lifetime and discount rate for evaluating grid development projects (ENTSO-E 2015). I assume over the 25-year period of the project, that the carbon price in each country equals the SCC, and that the SCC increases by €5 every five years. This is in line with the SCC projected by the EPA at a 3% discount rate (Executive Order No. 12,866 2016). Assuming the lines can be commissioned in 2025. At 2025, the SCC is €40, and by the end of the 25 years, the SCC is €60. The benefit of period t thus depends on the SCC and transmission capacity.

The results of the BCA for achieving the EU2030 interconnection target are shown in Table 7.

Table 7: Benefit-cost analysis of electricity interconnection

	DE-PL					
	5300 MW	DE share	PL share			
Benefit (B€)	57.78	100%	0%			
Cost(B€)	0.966					
Benefit-cost ratio	59.77					
	FR wind - ES wind			FR wind - ES solar		
	10700 MW	FR share	ES share	10700 MW	FR share	ES share
Benefit (B€)	21.83	97.31%	2.72%	34.28	78.82%	21.24%
Cost(B€)	12.53			12.53		
Benefit-cost ratio	1.74			2.74		

The results confirm that expanding the DE-PL and FR-ES interconnection generates positive net benefits, despite the high investment cost. However, the benefit-cost ratios should be interpreted with care since I only considered the first-order cost of investment, abstracting from subsequent operation and maintenance costs. Note that in the DE-PL case, the benefit-cost ratio of the transmission project is large. The benefit consists of the increased consumer surplus in Germany and the avoided investment cost in wind capacity. Whereas in the FR-ES case, the benefit-cost ratio is much smaller.

Table 7 also displays the share of the welfare benefit acquired in each country. It is straightforward that the benefits are unevenly shared between countries. Germany benefits more than Poland; France benefits more than Spain. In all three cases, the net-importers of electricity extract a higher share of the benefit. Knowing the shares of benefits can assist decision-making regarding the investment cost payment of the two countries for cross-border transmission projects.

6 Concluding remarks

The decarbonization of the power sector requires electricity generation to find alternatives to thermal power. However, the substitutability of renewables diminishes with intermittency. Electricity interconnection can potentially smooth the spatial intermittency of renewable production and make more efficient use of available generation technologies.

This paper provides an optimal investment and production model that focuses on electricity interconnection and studies whether interconnection with intermittent renewables always facilitates the penetration of renewable energies and reduces carbon emissions. The theoretical model shows that interconnection does not always lead to more renewables or lower emissions. When countries coordinate to maximize social welfare, subject to an exogenous SCC and transmission capacities, interconnection may decrease the social value for renewable investment and exacerbate carbon emissions if the SCC is low. Conversely, interconnection may expand renewable investments and decrease carbon emissions if the SCC is high. The results are driven by the competitiveness between renewables and thermal power. Since electricity is a homogeneous good, interconnection benefits whichever is the more efficient technology. At low carbon prices, thermal power is more competitive than renewables; therefore, renewable capacity decreases.

To simulate the impact of interconnection, I calibrate the model using data from four representative EU countries: Germany, Poland, France, and Spain. The simulations show that in a representative EU context, achieving the EU 2030 interconnection targets may increase carbon emissions for some countries. This is because currently, countries adopt different energy taxation schemes on top of the regional level emissions trading scheme. If the electricity market becomes more integrated, countries like Germany who adopts very high domestic electricity taxes can by cheaper electricity from the market. Consequently, Germany may increase its electricity consumption level and reduce investments in renewable capacity, which lead to more carbon emissions. This result implies that although interconnection is strictly welfare improving for the EU, carbon emissions do not necessarily decrease, unless the SCC is high.

From the welfare perspective, the benefit-cost analysis suggests a positive net-benefit from interconnection. But the interconnected countries share the net-benefit to varied extents. Currently in the EU, interconnection investments are shared between the interconnected countries and the European Commission.[26] The different benefit-cost ratios of projects and the unbalanced share of net benefit can shed lights on where the investment should be targeted and how the cost should be split between countries.

The optimal capacities, production, and consumption characterized in the model can be decentralized as a competitive market equilibrium if there is a global Pigouvian carbon tax equal to the SCC. Although a direct carbon tax is most efficient, the public has been reluctant to accept a direct tax. Therefore, most countries and regions including the EU and China are implementing revenue neutral policies, such as the emissions trading scheme. This model framework can also be adapted to consider other carbon policy instruments, such as cap-and-trade, renewable portfolio standard, and feed-in-tariffs for renewables.

In many cases, the interconnected countries and regions may adopt different carbon policies. For example, California implements stringent cap-and-trade programs, whereas its neighboring states in the southwestern and northwestern U.S. adopt few carbon policies. Since California is the largest electricity importer of all of the U.S. states, the externality from the uncontrolled emissions of other states may decrease the social welfare of California.[27] Future research is needed to investigate how interconnection with heterogeneous carbon policies affect total emissions.

[26] For example, the Biscay Gulf project between France and Spain receives €578 million from the EU, for an estimated cost of €1.7 billion.

[27] According to the U.S. Energy Information Administration, California imports on average 90 million MWh per year. https://www.eia.gov/todayinenergy/detail.php?id=38912

A Appendix

A.1 Proof of Lemma 1

Replacing K_{cf} with Q_c in problem 2, we have

$$
\begin{aligned}
\max_{Q_c, q^h_{cf}, K_i} \quad & S(Q_c) - (\kappa_c + \delta)(\nu q^h_{cf} - (1-\nu)Q_c) - r_f Q_c - f(K_i) \\
\text{s.t.} \quad & K_i + q^h_{cf} = Q_c \qquad [\lambda] \\
& Q_c \geq q^h_{cf} \qquad [\bar{\mu}] \\
& q^h_{cf} \geq 0 \qquad [\underline{\mu}] \\
& K_i \geq 0 \qquad [\gamma]
\end{aligned}
\tag{A.1}
$$

We can write the following Lagrangian:

$$
\begin{aligned}
\mathcal{L} =& S(Q_c) - \nu\Big((\kappa_c + \delta)q^h_{cf} - \lambda(Q_c - q^h_{cf} - K_i) - \underline{\mu} q^h_{cf} - \bar{\mu}(Q_c - q^h_{cf}) - \gamma K_i\Big) \\
& - (1-\nu)(\kappa_+ \delta)Q_c - f(K_i) - r_f Q_c
\end{aligned}
\tag{A.2}
$$

The first order conditions (focs) are:

$$\frac{\partial \mathcal{L}}{\partial Q_c} = S'(Q_c) + \lambda\nu - (1-\nu)(\kappa_c + \delta) - r_f = 0 \tag{A.3}$$

$$\frac{\partial \mathcal{L}}{\partial q^h_{cf}} = \underline{\mu} - \bar{\mu} - \lambda - \kappa_c - \delta = 0 \tag{A.4}$$

$$\frac{\partial \mathcal{L}}{\partial K_i} = \nu(\gamma - \lambda) - f'(K_i) = 0 \tag{A.5}$$

plus the complementary slackness conditions.

Substitute λ in equation A.5 by equation A.4: $\frac{f'(K_i)}{\nu} = \kappa_c + \delta + \bar{\mu} - \underline{\mu} + \gamma$, where $f'(K_i) = f'(K_i)$. If $\frac{f'(K_i)}{\nu} > \kappa_c + \delta$, thus $\bar{\mu} > 0$, $\underline{\mu} = 0$, $\gamma > 0$, $q^h_{cf} = Q_c$, $K_i = 0$, and $Q_c = D(\kappa_c + \delta + r_f)$.

If $\frac{f'(K_i)}{\nu} = \kappa_c + \delta$, $\bar{\mu} = 0$, $\underline{\mu} = 0$, $\gamma = 0$, $\lambda = \kappa_c + \delta$, $0 < q^h_{cf} < Q_c$, $K_i > 0$, and $Q_c = D(\kappa_c + \delta + r_f)$.

If $\frac{f'(K_i)}{\nu} < \kappa_c + \delta$, $\bar{\mu} = 0$, $\underline{\mu} > 0$, $\gamma = 0$, $\lambda = \frac{f'(K_i)}{\nu}$, $q^h_{cf} = 0$, and $K_i = Q_c = D((1-\nu)(\kappa_c + \delta) + f'(K_i) + r_f)$.

A.2 Proof of Lemma 2

Several simplifications can be made for problem 3. q^h_{jf} $\forall j$ can be replaced by the non-state-contingent demands. K_{cf} and K_{df} can be replaced by $Q_c - x^l$ and $Q_d + x^l$ respectively. Since K_t is not binding, the trade quantity is capped by the consumption in Clean and Dirty.

The simplified problem is as follows:

$$\begin{aligned}
\max_{\substack{Q_j, x^s, K_i \\ j=C,D,s=h,l}} \quad & S(Q_c) + S(Q_d) - \nu\big(\kappa_c(Q_c + x^h - K_i) + \kappa_d(Q_d - x^h) + \delta(Q_c + Q_d - K_i)\big) \\
& - (1-\nu)\big(\kappa_c(Q_c - x^l) + \kappa_d(Q_d + x^l) + \delta(Q_c + Q_d)\big) - r_f(Q_c + Q_d) - f(K_i) \\
\text{s.t.} \quad & K_i \le Q_c + x^h \qquad [\underline{\lambda}] \\
& x^h + x^l \le K_i \qquad [\bar{\lambda}] \\
& x^h \le Q_d \qquad [\bar{\mu}] \\
& x^h \ge -Q_c \qquad [\underline{\mu}] \\
& x^l \le Q_c \qquad [\xi] \\
& K_i \ge 0 \qquad [\eta]
\end{aligned} \tag{A.6}$$

The Lagrangian is:

$$\begin{aligned}
\mathcal{L} =& S(Q_c) + S(Q_d) - \nu\Bigg(\kappa_c(Q_c + x^h - K_i) + \kappa_d(Q_d - x^h) + \delta(Q_c + Q_d - K_i) \\
& - \bar{\lambda}(K_i - x^h - x^l) - \underline{\lambda}(Q_c + x^h - K_i) - \bar{\mu}(Q_d - x^h) - \underline{\mu}(x^h + Q_c) - \eta K_i\Bigg) \\
& - (1-\nu)(\kappa_c(Q_c - x^l) + \kappa_d(Q_d + x^l) + \delta(Q_c + Q_d) - \xi(Q_c - x^l)) \\
& - r_f(Q_c + Q_d) - f(K_i)
\end{aligned} \tag{A.7}$$

Taking the (focs):

$$\frac{\partial \mathcal{L}}{\partial Q_c} = S'(Q_c) - \kappa_c - \delta - r_f + \nu(\underline{\lambda} + \underline{\mu}) + (1-\nu)\xi = 0 \tag{A.8}$$

$$\frac{\partial \mathcal{L}}{\partial Q_d} = S'(Q_d) - \kappa_d - \delta - r_f + \nu\bar{\mu} = 0 \tag{A.9}$$

$$\frac{\partial \mathcal{L}}{\partial x^h} = -\nu(\kappa_c - \kappa_d + \bar{\lambda} - \underline{\lambda} + \bar{\mu} - \underline{\mu}) = 0 \tag{A.10}$$

$$\frac{\partial \mathcal{L}}{\partial x^l} = (1-\nu)(\kappa_c - \kappa_d - \xi) - \nu\bar{\lambda} = 0 \tag{A.11}$$

$$\frac{\partial \mathcal{L}}{\partial K_i} = \nu(\kappa_c + \delta + \bar{\lambda} - \underline{\lambda} + \eta) - f'(K_i) = 0 \tag{A.12}$$

plus the complementary slackness conditions.

Rearrange equation A.11 we get

$$\kappa_c - \kappa_d = \frac{\nu}{1-\nu}\bar{\lambda} + \xi \tag{A.13}$$

Given the assumption $\kappa_c > \kappa_d$, it must be $\bar{\lambda} > 0$, $\xi > 0$. Therefore $x^l = Q_c$ and $K_i = x^h + x^l$.

Equation A.12 and A.10 give us

$$\frac{f'(K_i)}{\nu} - (\kappa_d + \delta) = \underline{\mu} - \bar{\mu} + \eta \tag{A.14}$$

K_i and the direction of trade flow in the state h depend on comparison between the long-run marginal cost of renewable capacity and the marginal cost of thermal production. If $\frac{f'(K_i)}{\nu} > \kappa_d + \delta$, then $\underline{\mu} > 0$, $\bar{\mu} = 0$, $\eta > 0$. If $\frac{f'(K_i)}{\nu} = \kappa_d + \delta$, then $\underline{\mu} = 0$, $\bar{\mu} = 0$, $\eta = 0$. If $\frac{f'(K_i)}{\nu} < \kappa_d + \delta$, then $\underline{\mu} = 0$, $\bar{\mu} > 0$, $\eta = 0$. The optimal quantities thus follow.

A.3 Proof of Proposition 1

Proposition 1.i follows directly from Lemma 1 and 2 by looking at K^A_{jf} and K^F_{jf} $\forall j \in \{c, d\}$. For any value of the SCC, $K^A_{cf} = Q^A_c$ and $K^A_{df} = Q^A_d$, $K^F_{cf} = 0$ and $K^F_{df} = Q^F_c + Q^F_d$.

Proposition 1.ii is proved by comparing K^A_i to K^F_i. Denote $\Delta K_i = K^A_i - K^F_i$.

$$\Delta K_i = \begin{cases} 0 & \text{if} \quad \delta \leq \underline{\delta}^A \\ f'^{-1}(\nu(\kappa_c + \delta)) > 0 & \text{if} \quad \underline{\delta}^A < \delta \leq \underline{\delta}^F \\ f'^{-1}(\nu(\kappa_c + \delta)) - f'^{-1}(\nu(\kappa_d + \delta)) > 0 & \text{if} \quad \underline{\delta}^F < \delta \leq \bar{\delta}^A \\ D((1-\nu)(\kappa_c + \delta) + f'(K_i)^A + r_f) - f'^{-1}(\nu(\kappa_d + \delta)) & \text{if} \quad \bar{\delta}^A < \delta \leq \bar{\delta}^F \\ D((1-\nu)(\kappa_c + \delta) + f'(K_i)^A + r_f) - & \\ \qquad 2D((1-\nu)(\kappa_d + \delta) + r_f + f'(K_i)^F) < 0 & \text{if} \quad \delta > \bar{\delta}^F \end{cases}$$

Since $\Delta K_i < 0$ if $\delta \leq \bar{\delta}^A$, $\Delta K_i > 0$ if $\delta > \bar{\delta}^F$, and $\Delta K_i|_{\bar{\delta}^A < \delta \leq \bar{\delta}^F}$ is monotonically increasing in δ, it is straightforward that $\exists\ \hat{\delta} \in (\bar{\delta}^A, \bar{\delta}^F)$, such that $\Delta K_i = 0$ if $\delta = \hat{\delta}$.

Proposition 1.iii is proved by comparing Q^A_j to Q^F_j $\forall j \in \{c, d\}$. For the Dirty country, $Q^F_d > Q^A_d$ when $\delta > \bar{\delta}^F$, and $Q^F_d = Q^A_d$ when $\delta \leq \bar{\delta}^F$. For the Clean country, $Q^F_c > Q^A_c$ $\forall \delta \leq \hat{\delta}$. If $\delta > \hat{\delta}$, depending on the convexity of the cost function $f()$, $Q^A_c \gtreqless Q^F_c$ as shown below.

$$Q_c^A - Q_c^F = \begin{cases} D((1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f) - \\ \qquad D(\kappa_d+\delta+r_f) & \text{if} \quad \hat{\delta} < \delta \leq \bar{\delta}^F \\ D((1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f) - \\ \qquad D((1-\nu)(\kappa_d+\delta) + r_f + f'(K_i^F)) & \text{if} \quad \delta > \bar{\delta}^F \end{cases}$$

$Q_c^A - Q_c^F$ has the reverse sign as the difference between the retail prices $p_c^A - p_c^F$.

$$p_c^A - p_c^F = \begin{cases} (1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f - \\ \qquad (\kappa_d+\delta+r_f) & \text{if} \quad \hat{\delta} < \delta \leq \bar{\delta}^F \\ (1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f - \\ \qquad (1-\nu)(\kappa_d+\delta) - r_f - f'(K_i)^F & \text{if} \quad \delta > \bar{\delta}^F \end{cases}$$

$$p_c^A - p_c^F \begin{cases} > 0 & \text{if} \quad \hat{\delta} < \delta < \frac{(1-\nu)\kappa_c + f'(K_i)^A - \kappa_d}{\nu} \\ < 0 & \text{if} \quad \frac{(1-\nu)\kappa_c + f'(K_i)^A - \kappa_d}{\nu} < \delta < \frac{f'(K_i)^F - f'(K_i)^A}{1-\nu} - (\kappa_c - \kappa_d) \end{cases}$$

There may $\exists\, \mathring{\delta}$ such that the relationship between the autarky and free trade consumption level in the Clean country is reversed.

Proposition 1.iv is proved by comparing $E^A = \sum_{j,s} q_{jf}^{sA}$ to $E^F = \sum_{j,s} q_{jf}^{sF}$. Denote $\Delta E = E_F - E_A$.

$$\Delta E = \begin{cases} D(\kappa_d+\delta+r_f) - D(\kappa_c+\delta+r_f) > 0 & \text{if} \quad \delta \leq \underline{\delta}^A \\ D(\kappa_d+\delta+r_f) - D(\kappa_c+\delta+r_f) + \nu f'^{-1}(\kappa_c+\delta) > 0 & \text{if} \quad \underline{\delta}^A < \delta \leq \underline{\delta}^F \\ D(\kappa_d+\delta+r_f) - D(\kappa_c+\delta+r_f) - \\ \qquad \nu(f'^{-1}(\kappa_d+\delta) - f'^{-1}(\kappa_c+\delta)) > 0 & \text{if} \quad \underline{\delta}^F < \delta \leq \bar{\delta}^A \\ D(\kappa_d+\delta+r_f) - \nu f'^{-1}(\kappa_d+\delta) - \\ \qquad (1-\nu)D((1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f) > 0 & \text{if} \quad \bar{\delta}^A < \delta \leq \hat{\delta} \\ D(\kappa_d+\delta+r_f) - \nu f'^{-1}(\kappa_d+\delta) - \\ \qquad (1-\nu)D((1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f) & \text{if} \quad \hat{\delta} < \delta \leq \bar{\delta}^F \\ 2(1-\nu)D((1-\nu)(\kappa_d+\delta) + r_f + f'(K_i^F)) - \\ \qquad (1-\nu)D((1-\nu)(\kappa_c+\delta) + f'(K_i)^A + r_f) - \\ \qquad D(\kappa_d+\delta+r_f) < 0 & \text{if} \quad \delta \geq \bar{\delta}^F \end{cases}$$

Since $\Delta E > 0$ if $\delta \leq \hat{\delta}$, $\Delta E < 0$ if $\delta > \bar{\delta}^F$, and $\Delta E|_{\hat{\delta} < \delta \leq \bar{\delta}^F}$ is monotonically decreasing in

δ, then $\exists\, \tilde{\delta} \in (\hat{\delta}, \bar{\delta}^F)$, such that $\Delta E = 0$ if $\delta = \tilde{\delta}$.

A.4 Proof of Lemma 3

Rewrite the maximization problem by replacing the non-contingent demand constraints and K_f with Q_c:

$$\begin{aligned}
\max_{\substack{Q_c, q_f^s, K_i, x \\ s\in\{a,b,c\}}} \quad & 2\Big(S(Q_c) - \sigma_{hh}(\kappa_c+\delta)q_f^a - \sigma_{hl}(\kappa_c+\delta)(2Q_c - K_i) \\
& - \sigma_{ll}(\kappa_c+\delta)Q_c - r_f Q_c - f(K_i)\Big) \\
\text{s.t.} \quad & q_f^a + K_i \geq Q_c & [\lambda] \\
& Q_c \geq 2Q_c - K_i \geq 0 & [\bar{\phi}, \underline{\phi}] \\
& 0 \leq q_f^a \leq Q_c & [\underline{\mu}, \bar{\mu}] \\
& K_i \geq 0 & [\eta] \\
& x = \max\{K_i - Q_c, 0\} & [\xi] \\
& 0 \leq x \leq \min\{K_t, Q_c\} & [\underline{\gamma}, \bar{\gamma}]
\end{aligned} \tag{A.15}$$

The Lagrangian for the maximization problem:

$$\begin{aligned}
\mathcal{L} =& 2\Big(S(Q_c) - \sigma_{hh}(\kappa_c+\delta)q_f^a - \sigma_{hl}(\kappa_c+\delta)(2Q_c - K_i) - \sigma_{ll}(\kappa_c+\delta)Q_c - r_f Q_c \\
& - f(K_i) + \sigma_{hh}(\lambda(q_f^a + K_i - Q_c) + \underline{\mu} q_f^a + \bar{\mu}(Q_c - q_f^a)) \\
& + \sigma_{hl}(\underline{\gamma} x + \bar{\gamma}(\min\{K_t, Q_c\} - x) + \bar{\phi}(K_i - Q_c) + \underline{\phi}(2Q_c - K_i)) + \nu\eta K_i \\
& + \sigma_{hl}\xi(x - \max\{K_i - Q_c, 0\})\Big)
\end{aligned} \tag{A.16}$$

The focs are:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial Q_c} =& S'(Q_c) - (2\sigma_{hl} + \sigma_{ll})(\kappa_c+\delta) - r_f - \sigma_{hh}\lambda + \sigma_{hh}\bar{\mu} \\
& + \sigma_{hl}(\bar{\gamma}\mathbb{1}_{K_t > Q_c} + \underline{\phi} + \xi) = 0
\end{aligned} \tag{A.17}$$

$$\frac{\partial \mathcal{L}}{\partial q_f^a} = -\sigma_{hh}(\kappa_c + \delta - \lambda - \underline{\mu} + \bar{\mu}) = 0 \tag{A.18}$$

$$\frac{\partial \mathcal{L}}{\partial K_i} = \sigma_{hl}(\kappa_c + \delta - \underline{\phi} + \bar{\phi} - \xi\mathbb{1}_{K_i > Q_c}) - f'(K_i) + \sigma_{hh}\lambda + \nu\eta = 0 \tag{A.19}$$

$$\frac{\partial \mathcal{L}}{\partial x} = \sigma_{hl}(\underline{\gamma} - \bar{\gamma} + \xi) = 0 \tag{A.20}$$

plus the complementary slackness conditions.

From equations A.18, A.19, we can obtain

$$f'(K_i) - \nu(\kappa_c + \delta) = \nu\eta + \sigma_{hh}(\bar{\mu} - \underline{\mu}) + \sigma_{hl}(\bar{\phi} - \underline{\phi} - \xi \mathbb{1}_{K_i > Q_c})$$

When $K_t > 0$,

1. If $f'(K_i) > \nu(\kappa_c + \delta)$, $\eta > 0$, $\bar{\mu} > 0$, $\underline{\mu} = 0$, $\bar{\phi} > 0$, $\underline{\phi} = 0$.

   Thus $K_i^T = 0$, $q_f^{aT} = Q_c^T = K_f^T$, $x^T = 0$, and $Q_c^T = D(\kappa_c + \delta + r_f)$. The threshold $\delta = \frac{r_i}{\nu} - c$.

2. If $f'(K_i) = \nu(\kappa_c + \delta)$, $\eta = 0$, $\bar{\mu} = 0$, $\underline{\mu} = 0$, $\bar{\phi} = 0$, $\underline{\phi} = 0$.

   There are two sub-cases:

   (a) $K_i^T \leq Q_c^T$
   $q_f^{aT} = Q_c^T - K_i^T$, $K_i^T = f'^{-1}(\nu(\kappa_c + \delta))$, $x^T = 0$, and $Q^T = D(\kappa_c + \delta + r_f)$. The threshold δ for $K_i^T = Q_c^T$ is denoted $\hat{\delta}$ and solves for $f'^{-1}(\nu(\kappa_c + \hat{\delta})) = D(\kappa_c + \hat{\delta} + r_f)$.

   (b) $K_i^T > Q_c^T$
   $q_f^{aT} = 0$, $x^T = K_i^T - Q^T$, $K_i^T = f'^{-1}(\nu(\kappa_c + \delta))$ and $Q^T = D(\kappa_c + \delta + r_f)$. The threshold δ for $K_i^T = Q_c^T + K_t$ is denoted $\bar{\delta}^T$ and solves for $f'^{-1}(\nu(c + \bar{\delta}^T)) = D(c + \bar{\delta}^T + r_f) + K_t$ and $\frac{\partial \bar{\delta}^T}{\partial K_t} \geq 0$.

3. If $f'(K_i) < \nu(\kappa_c + \delta)$, $\eta = 0$, $\bar{\mu} = 0$, $\underline{\mu} > 0$, $\bar{\phi} = 0$, $\underline{\phi} > 0$, $\xi > 0$.

   In this case, $q_f^{aT} = 0$, $x^T = \max\{K_t, Q_c^T\}$, $K_i^T = Q_c^T + x^T$, and $Q_c^T = D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i^T))$. This cases occurs when $\delta > \bar{\delta}^T$.

   If $K_t > Q^T$, $K_i^T = 2Q_c^T$ and $Q_c^T = D(\sigma_{ll}(\kappa_c + \delta) + r_f + f'(K_i^T))$.

A.5 Proof of Proposition 2

By comparing Lemma 1 and Lemma 3, it is straightforward that when $\delta \leq \bar{\delta}^A$, the optimal capacities and consumption have the exact same expressions. Therefore, trade is equivalent as autarky.

When $\delta > \bar{\delta}^A$, when $f'(K_i^T) = \kappa_c + \delta$, there is now more renewable capacity than local demand: $Q_c^T = D(\kappa_c + \delta + r_f) < K_i^T$. $\forall\ \delta > \bar{\delta}^A$, $Q_c^T < Q_c^A = D((1-\nu)(\kappa_c + \delta) + r_f +$

$f'(K_i^A))$. Therefore, renewable capacities increases with trade and consumption decreases with trade.

For carbon emissions, $E^A = 2(1-\nu)Q_c^A$, and $E^T = 2(1-\nu)Q_c^T - 2\sigma_{hl}K_i < E^A$. Thus, carbon emissions also decreases with trade.

To check how Q_c^T, K_i^T change with relaxed K_t and ρ, we need the following system of equations if $K_t < Q^T$:

$$\begin{cases} S'(Q_c^T) = (1-\nu)(\kappa_c + \delta) + r_f + f'(K_i) \\ K_i = Q_c^T + K_t \end{cases}$$

They can be rewritten as implicit functions $\boldsymbol{F}(Q_c^T, K_i; K_t) = 0$. Rewrite in matrix form:

$$\begin{bmatrix} S''(Q_c^T) & -f''(K_i^T) \\ -1 & 1 \end{bmatrix} \begin{bmatrix} \frac{\partial Q^c}{\partial K_t} \\ \frac{\partial K_i}{\partial K_t} \end{bmatrix} = - \begin{bmatrix} 0 \\ -1 \end{bmatrix}$$

The determinant of the Jacobians

$$|\boldsymbol{J}| = S''(Q_c^T) - f''(K_i^T) < 0 \tag{A.21}$$

$$|\boldsymbol{J}_{Q_c K_t}| = f''(K_i^T) < 0 \tag{A.22}$$

$$|\boldsymbol{J}_{K_i K_t}| = -S''(Q^T) > 0 \tag{A.23}$$

By applying Cremer's rule,

$$\frac{\partial Q_c^T}{\partial K_t} = -\frac{|\boldsymbol{J}_{Q_c K_t}|}{|\boldsymbol{J}|} < 0$$

$$\frac{\partial K_i^T}{\partial K_t} = -\frac{|\boldsymbol{J}_{K_i K_t}|}{|\boldsymbol{J}|} > 0$$

Therefore, Q_c^T decreases and K_i^T increases with more transmission capacity.

If $K_t > Q^T$, Q_c^T and K_i^T solve

$$\begin{cases} S'(Q_c^T) = \sigma_{ll}(\kappa_c + \delta) + r_f + f'(K_i^T) \\ K_i^T = 2Q_c^T \end{cases}$$

They can be written as implicit functions of ρ: $\boldsymbol{F}(Q_c^T, K_i^T; \rho) = 0$. Rewrite in matrix form:

$$\begin{bmatrix} S''(Q^T) & -f''(K_i^T) \\ -2 & 1 \end{bmatrix} \begin{bmatrix} \frac{\partial Q_c}{\partial \rho} \\ \frac{\partial K_i}{\partial \rho} \end{bmatrix} = - \begin{bmatrix} -\nu(1-\nu)(\kappa_c + \delta) \\ 0 \end{bmatrix}$$

$$|\boldsymbol{J}| = S''(Q_c^T) - 2f''(K_i^T) < 0 \tag{A.24}$$
$$|\boldsymbol{J}_{Q_c\rho}| = -\nu(1-\nu)(\kappa_c + \delta) - 2f''(K_i^T) < 0 \tag{A.25}$$
$$|\boldsymbol{J}_{K_i\rho}| = -2\nu(1-\nu)(\kappa_c + \delta) < 0 \tag{A.26}$$

By applying Cremer's Rule, we know that Q_c^T and K_i^T decrease as ρ increases.

A.6 Proof of Corollary 1

The carbon emissions in the four cases in Lemma 3 are:

i $E = 2Q_c^T = 2D(\kappa_c + \delta + r_f)$

ii $E = 2Q_c^T - \nu K_i^T) = 2(D(\kappa_c + \delta + r_f) - \nu f'^{-1}(\kappa_c + \delta)$

iii $E = 2(1-\nu)Q_c^T - \sigma_{hl}(K_i^T - Q_c^T) = 2((1-\sigma_{hh})D(\kappa_c + \delta + r_f) - \sigma_{hl} f'^{-1}(\kappa_c + \delta$

iv (a) $K_t < Q_c^T$: $E = 2((1-\nu)Q_c^T - \sigma_{hl}K_t)$

(b) $K_t \geq Q_c^T$: $E = 2\sigma_{ll}Q_c^T$

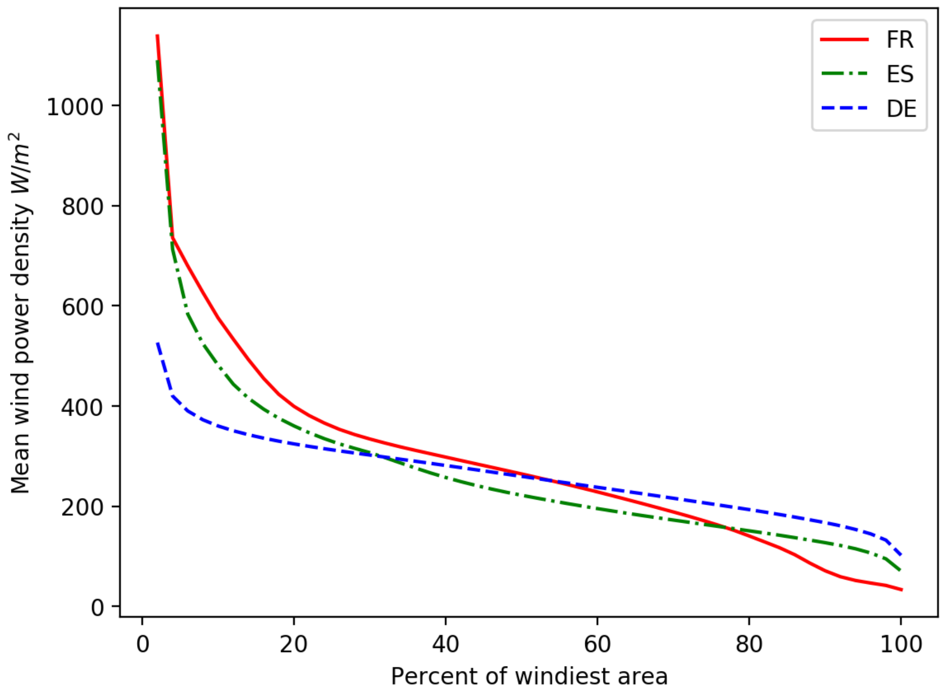
The correlation coefficient affects carbon emissions in cases iii and iv. For iii, $\frac{\mathrm{d}E}{\mathrm{d}\rho} = 2\nu(1-\nu)(f'^{-1}(\kappa_c + \delta) - D(\kappa_c + \delta + r_f)) > 0$. For iv(a), $\frac{\mathrm{d}E}{\mathrm{d}\rho} = \nu(1-\nu)f'^{-1}(\kappa_c + \delta) > 0$. For iv(b), $\frac{\mathrm{d}E}{\mathrm{d}\rho} = 2\sigma_{ll}\frac{\partial Q_c^T}{\partial \rho} + 2\nu(1-\nu)Q_c^T = -2\sigma_{ll}\frac{|\boldsymbol{J}_{Q\rho}|}{|\boldsymbol{J}|} + 2\nu(1-\nu)Q_c^T > 0$. In all three cases, emissions increase as ρ increases.

A.7 Fitting the marginal cost curve of renewables

The convexity in marginal cost of renewable capacity can be attributed to several factors, including the location of wind farms, land cost, installation and labor cost, etc. In this simulation, I focus on the first-order factor of geographical locations. As renewable resources are not uniformly distributed across space, the wind turbines and solar panels at different locations will generate various levels of output, i.e. capacity factors. Therefore, there is an inverse relationship between the renewable power and the levelized cost of renewables generated electricity.

Wind power To exploit this inverse relationship for wind power, I use the wind power density data from the Global Wind Atlas. Figure A.1 shows the incremental mean wind power density in each percentile. I then use the following formula to obtain the marginal

Figure A.1: Incremental Mean Wind Power Density



cost values for each percentile of wind areas.

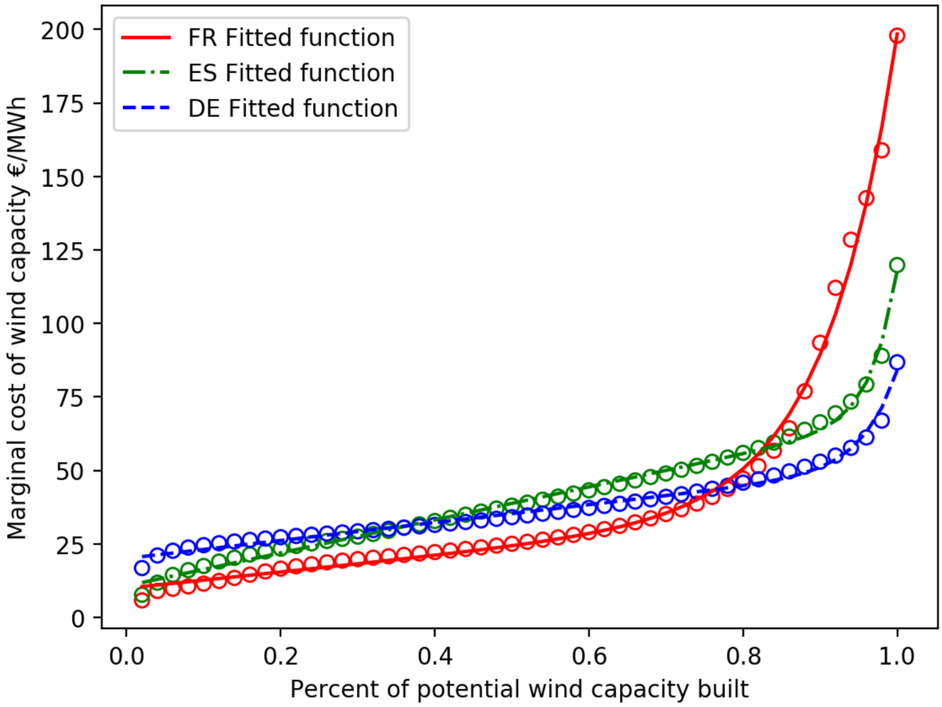
$$\text{Marginal percentile capcity cost} = \frac{\text{Unit investment cost} * \text{Country average capacity factor} * \text{Max global wind density}}{\text{Percentile wind power density}} \tag{A.27}$$

The wind power density is the values obtained in Figure A.1; the unit investment cost for each country is taken from the IEA (2015) report; the country average capacity factor is calculated using actual generation data from ENTSO-E; and the Max global wind density is taken from the maximum wind density in the Global Wind Atlas data. The marginal cost values are then scatter plotted in Figure A.2. To obtain the marginal cost curve, I fit a function to the data points. $r_i = \alpha_1 e^{\alpha_2 x} + \alpha_3 x + \alpha_4$ fits well with the data, where x is the percentile of wind capacity installed. The lines in Figure A.2 shows the fitted marginal cost curves. The corresponding functions are thus used in the simulation.

Solar Power Similarly, I fit the solar power marginal cost curve for Spain using solar power output data obtained from Solargis, and land use data obtained from GeoNetwork. I assume that solar PV panel can be only put on the land areas in Spain which are classified as artificial and bare soil. I then map out the solar PV output intensity in these locations (Figure A.3).

I use the following equation to obtain the marginal capacity cost for each percentile of

Figure A.2: Fitted wind capacity marginal cost curve



potential solar capacity.

$$\begin{aligned}&\text{Marginal percentile capcity cost} = \\ &\frac{\text{Unit investment cost * Country average capacity factor}}{\text{Percentile PV output/24}}\end{aligned} \tag{A.28}$$

The unit investment cost is taken from the IEA (2015) report; the country average capacity factor is calculated using actual generation data from ENTSO-E, the percentile PV output is calculated with data from Solargis. The fitted marginal cost curve has the same functional form as the wind case, with different parameter values (Figure A.4).[28]

[28] Python and R code are available upon request.

Figure A.3: Solar PV output in Spain for suitable locations

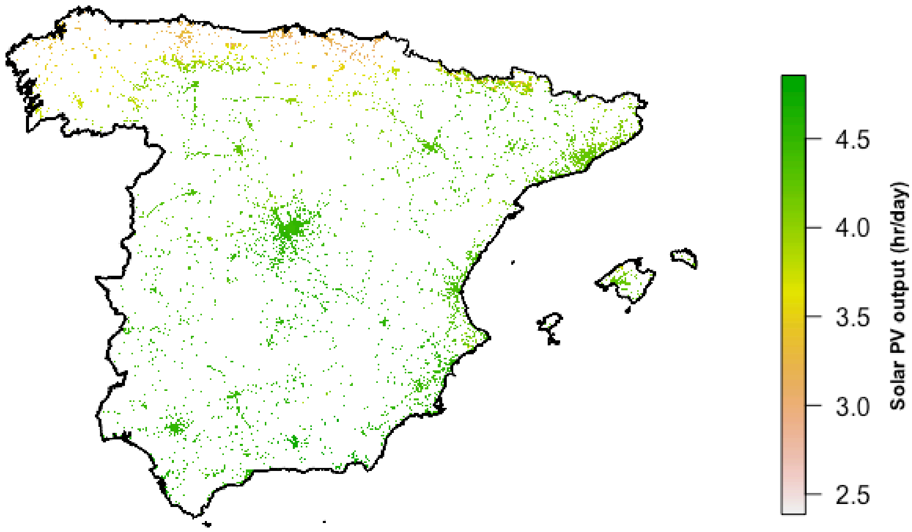
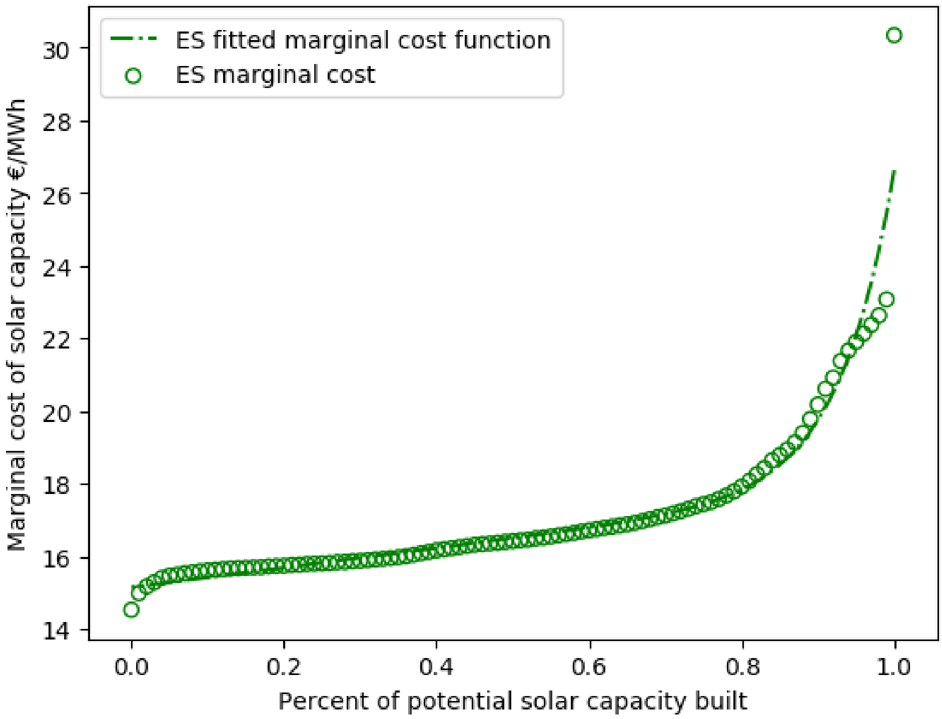


Figure A.4: Fitted solar capacity marginal cost curve



A.8 Extension: Clean-Dirty constrained interconnection

The simplified problem 3 with constrained transmission ($K_t < \min\{Q_c, Q_d\}$) is as follows:

$$
\begin{aligned}
\max_{\substack{Q_j, x^s, K_i \\ j=c,d, s=h,l}} \quad & S(Q_c) + S(Q_d) - \nu\big(\kappa_c(Q_c + x^h - K_i) + \kappa_d(Q_d - x^h) + \delta(Q_c + Q_d - K_i)\big) \\
& - (1-\nu)\big(\kappa_c(Q_c - x^l) + \kappa_d(Q_d + x^l) + \delta(Q_c + Q_d)\big) - r_f(Q_c + Q_d) - f(K_i) \\
\text{s.t.} \quad & K_i \le Q_c + x^h \qquad [\underline{\lambda}] \\
& x^h + x^l \le K_i \qquad [\bar{\lambda}] \\
& x^h \le K_t \qquad [\bar{\mu}] \\
& x^h \ge -K_t \qquad [\underline{\mu}] \\
& x^l \le K_t \qquad [\xi] \\
& K_i \ge 0 \qquad [\eta]
\end{aligned}
\tag{A.29}
$$

The Lagrangian is:

$$
\begin{aligned}
\mathcal{L} =& S(Q_c) + S(Q_d) - \nu\Bigg(\kappa_c(Q_c + x^h - K_i) + \kappa_d(Q_d - x^h) + \delta(Q_c + Q_d - K_i) \\
& - \bar{\lambda}(K_i - x^h - x^l) - \underline{\lambda}(Q_c + x^h - K_i) - \bar{\mu}(K_t - x^h) - \underline{\mu}(x^h + K_t) - \eta K_i\Bigg) \\
& - (1-\nu)(\kappa_c(Q_c - x^l) + \kappa_d(Q_d + x^l) + \delta(Q_c + Q_d) - \xi(K_t - x^l)) \\
& - r_f(Q_c + Q_d) - f(K_i)
\end{aligned}
\tag{A.30}
$$

Taking the focs:

$$\frac{\partial \mathcal{L}}{\partial Q_c} = S'(Q_c) - \kappa_c - \delta - r_f + \nu\underline{\lambda} = 0 \tag{A.31}$$

$$\frac{\partial \mathcal{L}}{\partial Q_d} = S'(Q_d) - \kappa_d - \delta - r_f = 0 \tag{A.32}$$

$$\frac{\partial \mathcal{L}}{\partial x^h} = -\nu(\kappa_c - \kappa_d + \bar{\lambda} - \underline{\lambda} + \bar{\mu} - \underline{\mu}) = 0 \tag{A.33}$$

$$\frac{\partial \mathcal{L}}{\partial x^l} = (1-\nu)(\kappa_c - \kappa_d - \xi) - \nu\bar{\lambda} = 0 \tag{A.34}$$

$$\frac{\partial \mathcal{L}}{\partial K_i} = \nu(\kappa_c + \delta + \bar{\lambda} - \underline{\lambda} + \eta) - f'(K_i) = 0 \tag{A.35}$$

plus the complementary slackness conditions.

Rearranging equation A.35 we have

$$\frac{f'(K_i)}{\nu} - (\kappa_c + \delta) = \bar{\lambda} - \underline{\lambda} + \eta, \tag{A.36}$$

and equations A.33 and A.35 give

$$\frac{f'(K_i)}{\nu} - (\kappa_d + \delta) = \underline{\mu} - \bar{\mu} + \eta, \tag{A.37}$$

By equation A.34, we have $\kappa_c - \kappa_d = \xi + \frac{\nu}{1-\nu}\bar{\lambda}$. Since $\kappa_c > \kappa_d$ by assumption, then $\xi > 0$ and $\bar{\lambda} > 0$, so $x^l = K_t$. From equation A.33, we get that $Q_d = D(\kappa_d + \delta + r_f)$, $\forall K_t, \delta$.

Therefore, we only need to pin down Q_c, K_i, and x^h. Equation A.36 and A.37 jointly determine the threshold levels of SCC for renewable capacities and the direction of trade flow in state h. Consequently, all of the other choice variables can then be pinned down through the value of the multipliers. Therefore, for each value of K_t, there exists a set of threshold δ, on which the optimal capacities, consumption levels, and trade quantities depend.

Solving the focs, I obtain the following results:

1. $\delta < \frac{r_i}{\nu} - \kappa_c$

   In this case, $\bar{\lambda} > 0$, $\underline{\lambda} = 0$, $\eta > 0$, $\bar{\mu} = 0$, $\underline{\mu} > 0$. Therefore, $K_i = 0$, $x^h = -K_t$. There is no investment in the renewables and both countries produce with thermal power. Depending on the transmission capacity, there are two cases.

   (a) $0 < K_t < Q_c^A$

   When when there is constrained transmission, $Q_c = Q_c^A$, $K_{df} = Q_d^A + K_t$, $K_{cf} = Q_c^A - K_t$. The shadow value of allowing for relaxing the transmission constraint is $\lambda = \lambda^A$. The retail price p_c and p_d is the same as under autarky. Although transmission does not affect the optimal level of consumption in both countries, it shifts production to the low-cost country. Thus, the optimal thermal power capacity increases in the Dirty country and decreases in the Clean country.

   (b) $Q_c^A \leq K_t < Q_c^F$

   When the transmission capacity constraint exceeds the autarky level of demand in Q_c, then $\lambda > 0$ and $\mu > 0$. $Q_c = K_t$, $K_{df} = Q_d^A + K_t$, $K_{cf} = 0$. The shadow value of increasing transmission capacity is $\lambda = \kappa_c - \kappa_d - \mu$., where $\mu = \kappa_c + \delta + r_f - S'(K_t)$. The retail price in the Clean country decrease to $p_C = S'(K_t)$.

In this case, the Clean country can import more electricity than the autarky demanded at a lower price. All the thermal power production will take place in the Dirty country.

2. $\frac{r_i}{\nu} - \kappa_c \leq \delta < \frac{r_i}{\nu} - \kappa_d$
In this case, $\bar{\lambda} = 0$, $\underline{\lambda} \geq 0$, $\eta \geq 0$, $\bar{\mu} = 0$, $\underline{\mu} > 0$, $\xi > 0$. So $K_i \leq 0$, $x^h = -K_t$.

   (a) If $0 < K_t < \underline{Q}_c^A - K_i^A$, the Clean country will import up to the transmission capacity in state h and produce the residual demand with both renewables and thermal power. So $q_{cf}^h = \underline{Q}_c^A - K_i^A - K_t$. And in state l, C will import up to the transmission capacity. Thus $K_{cf} = \underline{Q}_c^A - K_t$, $K_{df} = Q_d + K_t$. $\underline{Q}_c^A = D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i^A))$, $K_i^A = f'^{-1}(\nu(\kappa_c + \delta))$.
   The shadow value of expanding transmission in both states are $\underline{\mu} = \xi = \kappa_c - \kappa_d$.

   (b) If $\underline{Q}_c^A - K_i^A \leq K_t < \bar{Q}_c^A$, the Clean country will import up to transmission capacity in state l and produce the residual demand with only renewables. So $\bar{Q}_c^A = D((1-v)(\kappa_c + \delta) + r_f + f'(K_i)) > \underline{Q}_c^A$, $K_i = \bar{Q}_c^A - K_t$, $q_{cf}^h = 0$, $K_{cf} = \bar{Q}_c^A - K_t$, $K_{df} = Q_d + K_t$.
   The shadow value of allowing for transmission in state h is $\underline{\mu} = \frac{f'(K_i^A)}{\nu} - (\kappa_d + \delta)$, and in state l is $\xi = \kappa_c - \kappa_d$.

   (c) If $\bar{Q}_c^A \leq K_t < \underline{Q}_c^T$, C will import full transmission capacity in both states. $Q_c = K_t$, $K_i = 0$, $K_{cf} = 0$, $K_{df} = Q_d + K_t$, and $p_c = \kappa_d + \delta + r_f + \underline{\mu}$, where $\underline{\mu} = \xi = S'(K_t) - (\kappa_d + \delta + r_f)$ is the shadow value for increasing transmission capacity.

Thus, given this range of δ, country C decreases its investment in renewables with gradual opening to trade and increases its level of consumption.

3. $\frac{r_i}{\nu} - \kappa_d \leq \delta < \hat{\delta}(K_t)$
In this case, the Clean country will have some renewable in state w regardless of the level of K_t. $\bar{\lambda} = 0$, $\underline{\lambda} > 0$, $\eta' = 0$, $\bar{\mu} = 0$, $\underline{\mu} \geq 0$, $\xi > 0$. So $K_i > 0$, $x^h \geq -K_t$. The threshold value of $\hat{\delta}(K_t)$ is such that renewable production covers the full demand of C in state h, $\hat{\delta}(K_t)|_{x^h=0} = \frac{f'(K_i)}{\nu} - \kappa_d$, where $K_i = Q_c$. In this case, country C does not have excess supply of renewables in state h that is cheaper than the thermal power in the Dirty country.

   (a) If $0 < K_t < Q_c^A$, there exist a threshold $\hat{K}_t(\delta)$ such that if $K_t < \hat{K}_t(\delta)$ $x^h = -K_t$, otherwise, $x^h > -K_t$, i.e. in state w, the transmission constraint is not binding. $\hat{K}_t(\delta)$ is the solution to $K_t = Q_c - f'^{-1}(\nu(\kappa_d + \delta))$.

   - If $K_t < \hat{K}_t(\delta)$, then $x^h = -K_t$, $\frac{f'(K_i)}{\nu} = \kappa_c + \delta$, $\underline{\mu} = \xi = \kappa_c - \kappa_d$. $Q_c = D(\kappa_c + \delta + r_f)$, $q_{cf}^h = Q_c - K_t - K_i$. $K_{cf} = Q_c - K_t$, $K_{df} = Q_d + K_t$.

- If $K_t \geq \hat{K}_t(\delta)$, then $x^h = Q_c - K_i$, where $K_i = f'^{-1}(\nu(\kappa_d + \delta))$. Here, $\underline{\mu} = 0$, $Q_c = D((1-\nu)\kappa_c + \nu\kappa_d + \delta + r_f)$, $p_C = (1-\nu)\kappa_c + \nu\kappa_d + \delta + r_f$, $q^h_{cf} = 0$, $K_{cf} = Q_c - K_t$, $K_{df} = Q_d + K_t$.

(b) If $Q^A_c \leq K_t < Q^T_c$, then $Q_c = K_t$, $p_C = S'(K_t)$, $\frac{f'(K_i)}{\nu} = \kappa_d + \delta$, $\underline{\mu} = \xi = S'(K_t) - \kappa_d - \delta - r_f$, $q^h_{cf} = 0$, $K_{cf} = 0$, $K_{df} = Q_d + K_t$.

4. $\hat{\delta}(K_t) \leq \delta < \bar{\delta}(K_t)$

In this case, the Clean country exports in state h its excess supply to the Dirty country. $\bar{\lambda} = 0$, $\underline{\lambda} > 0$, $\eta' = 0$, $\bar{\mu} \geq 0$, $\underline{\mu} = 0$, $\xi > 0$. So $x^h \leq K_t$. The threshold value of $\bar{\delta}(K_t)$ such that renewable export is equal to the transmission capacity ($K_i = Q_c + K_t$) is $\bar{\delta}(K_t)|_{x^h = K_t} = \frac{f'(K_i)}{\nu} - \kappa_d$, where $f'(K_i) = f'(D((p_c(K_t)) + K_t)$.

(a) If $0 < K_t < Q^A_c$, renewable capacity will be determined by $\frac{f'(K_i)}{\nu} = \kappa_d + \delta$. Therefore, $x^h = K_i - Q_c$. $Q_c = D((1-\nu)\kappa_c + \nu\kappa_d + \delta + r_f$. $q^h_{cf} = 0$, $q^h_{df} = Q_d + Q_c - K_i$, $K_{cf} = Q_c - K_t$, $K_{df} = Q_d + K_t$. The shadow value of transmission in state h is $\bar{\mu} = 0$ and in state l is $\xi = \kappa_c - \kappa_d$.

(b) If $Q^A_c \leq K_t < Q^T_c$, then $Q_c = K_t$, $p_C = S'(K_t)$, $\frac{f'(K_i)}{\nu} = \kappa_d + \delta$, $\bar{\mu} = 0$, $\xi = S'(K_t) - \kappa_d - \delta - r_f$, $q^h_{cf} = 0$, $q^h_{df} = Q_d + Q_c - K_i$, $K_{cf} = 0$, $K_{df} = Q_d + K_t$.

5. $\bar{\delta}(K_t) \leq \delta$

In this case, the Clean country exports in state h up to the transmission capacity. $\bar{\lambda} = 0$, $\underline{\lambda} > 0$, $\eta = 0$, $\bar{\mu} > 0$, $\underline{\mu} = 0$, $\xi > 0$. So $\frac{f'(K_i)}{\nu} < \kappa_d + \delta$, $x^h = K_t$.

(a) If $K_t < Q_c$, then $Q_c = D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i))$, $Q_d = D(\kappa_d + \delta + r_f)$, $x^h = x^l = K_t$, $K_i = Q_c + K_t$, $q^h_{cf} = 0$, $q^h_{df} = Q_d - K_t$, $K_{cf} = Q_c - K_t$, $K_{df} = Q_d + K_t$, $\bar{\mu} = \kappa_d + \delta - \frac{f'(K_i)}{\nu}$, $\xi = \kappa_c - \kappa_d$.

(b) If $Q_c \leq K_t < Q_d$, then $Q_c = K_t$, $Q_d = D(\kappa_d + \delta + r_f)$, $\bar{\mu} = \frac{f'(K_i)}{\nu} - \kappa_d - \delta$, $\xi = S'(K_t) - \kappa_d - \delta - r_f$, $q^h_{cf} = 0$, $q^h_{df} = Q_d - K_t$, $K_{cf} = 0$, $K_{df} = Q_d + K_t$.

(c) If $Q_d \leq K_t < Q^T_c = Q^T_d$, then $Q_c = K_t$, $Q_d = K_t$, $\bar{\mu} = \xi = S'(K_t) - (1 - \nu)(\kappa_d + \delta) - r_f - f'(K_i)$, $q^h_{cf} = 0$, $q^h_{df} = 0$, $K_{cf} = 0$, $K_{df} = 2K_t$.

The full results are shown in Figure A.5 and Table A.1.

A.8.1 Carbon emissions of constrained Clean-Dirty interconnection

Comparative statics can be derived with respect to the autarky level of emission, to see how expanding transmission affect carbon emissions (Figure A.6 and Table A.2).

Figure A.5: The optimal consumption level given different transmission capacity and carbon price

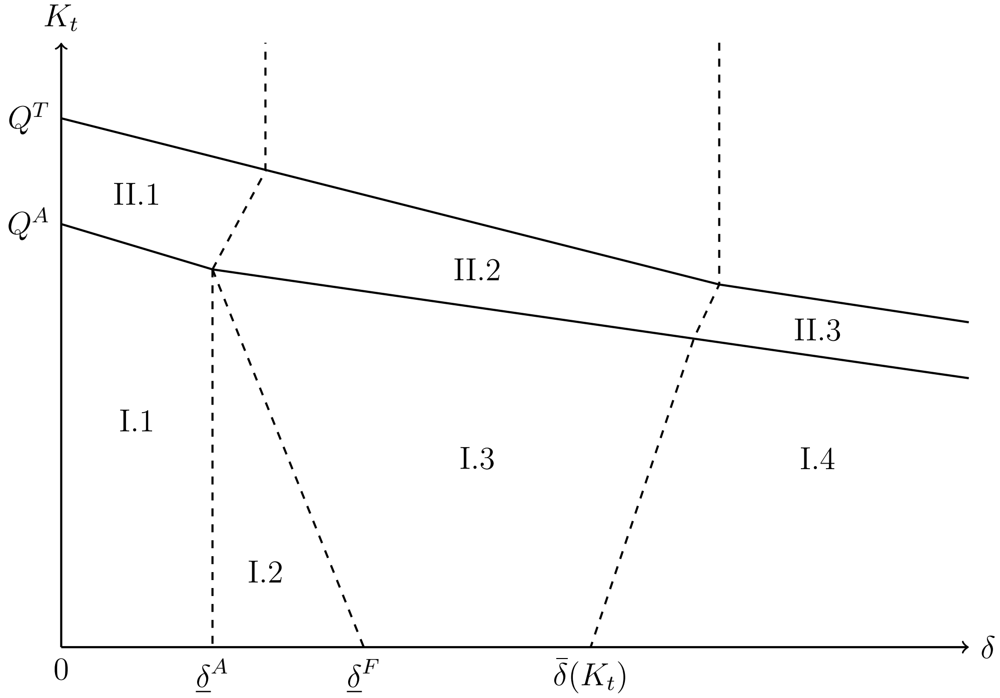


Table A.1: Summary statistics of optimal consumption, capacity and emission levels in Clean-Dirty interconnection

	I.1	I.2	I.3	I.4
Q_c	$D(\kappa_c+\delta+r_f)$	$D(\kappa_c+\delta+r_f)$	$D((1-\nu)\kappa_c+\nu\kappa_d+\delta+r_f)$	$D((1-\nu)\kappa_c+\delta+r_f+f'(K_i))$
K_{cf}	Q_c-K_t	Q_c-K_t	Q_c-K_t	Q_c-K_t
q^h_{cf}	Q_c-K_t	$Q_c-K_t-K_i$	0	0
K_i	0	$f'^{-1}(\nu(\kappa_c+\delta))$	$f'^{-1}(\nu(\kappa_d+\delta))$	K_t+Q_c
Q_d	$D(\kappa_d+\delta+r_f)$	$D(\kappa_d+\delta+r_f)$	$D(\kappa_d+\delta+r_f)$	$D(\kappa_d+\delta+r_f)$
K_{df}	Q_d+K_t	Q_d+K_t	Q_d+K_t	Q_d+K_t
q^h_{df}	Q_d+K_t	Q_d+K_t	$Q_d+Q_c-K_i$	$Q_d+Q_c-K_i$
E	Q_c+Q_d	$Q_c+Q_d-\nu K_i$	$Q_c+Q_d-\nu K_i$	$Q_c+Q_d-\nu K_i$
	II.1	**II.2**	**II.3**	
Q_c	K_t	K_t	K_t	
K_{cf}	0	0	0	
q^h_{cf}	0	0	0	
K_i	0	$f'^{-1}(\nu(\kappa_d+\delta))$	$2K_t$	
Q_d	$D(\kappa_d+\delta+r_f)$	$D(\kappa_d+\delta+r_f)$	$D(\kappa_d+\delta+r_f)$	
K_{df}	Q_d+K_t	Q_d+K_t	Q_d+K_t	
q^h_{df}	Q_d+K_t	$Q_d+K_t-K_i$	Q_d-K_t	
E	K_t+Q_d	$K_t+Q_d-\nu K_i$	$\nu(Q_d-K_t)+(1-\nu)(K_t+Q_d)$	

Figure A.6: Change in carbon emissions with respect to autarky Net emission level $\Delta E = E(K_t) - E^A$. The values for each range are listed in Table A.2.

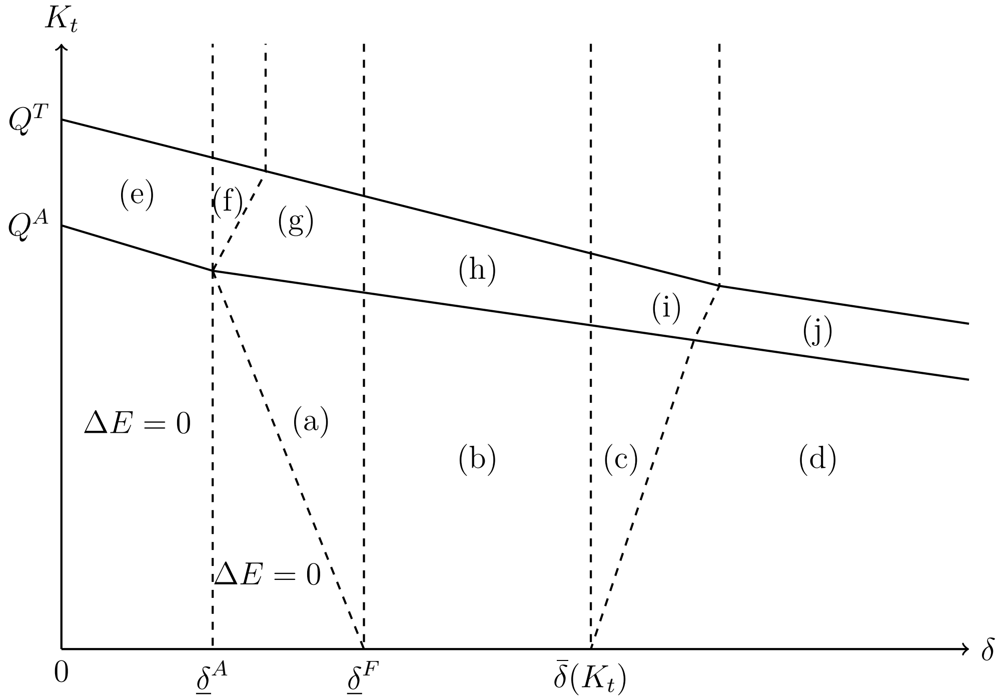


Table A.2: Net carbon emission levels of constraint Clean-Dirty interconnection

	ΔE	$\gtreqless 0$	$\frac{\partial \Delta E}{\partial K_t}$
(a)	$D((1-\nu)\kappa_c + \nu\kappa_d + \delta + r_f) - D(\kappa_c + \delta + r_f) - \nu\bar{K}(F(\nu(\kappa_d + \delta)) - F(\nu(\kappa_c + \delta)))$	> 0	$= 0$
(b)	$D((1-\nu)\kappa_c + \nu\kappa_d + \delta + r_f) - D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i))$ $-\nu\bar{K}(F(\nu(\kappa_d + \delta)) - F(f'(K_i)))$	> 0	$= 0$
(c)	$D((1-\nu)\kappa_c + \nu\kappa_d + \delta + r_f) - D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i))$ $-\nu\bar{K}(F(\nu(\kappa_d + \delta)) - F(f'(K_i)))$	< 0	$= 0$
(d)	$D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i)(Q_c + K_t)) - D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i)(Q_c))$ $-\nu\bar{K}(F(f'(K_i)(Q_c + K_t)) - F(f'(K_i)(Q_c)))$	< 0	< 0
(e)	$K_t - D(\kappa_c + \delta + r_f)$	> 0	> 0
(f)	$K_t - D(\kappa_c + \delta + r_f) + \nu f'^{-1}(\nu(\kappa_c + \delta))$	> 0	> 0
(g)	$K_t - D(\kappa_c + \delta + r_f) - \nu\bar{K}(F(\nu(\kappa_d + \delta)) - F(\nu(\kappa_c + \delta)))$	> 0	> 0
(h)	$K_t - D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i)) - \nu\bar{K}(F(\nu(\kappa_d + \delta)) - F(f'(K_i)))$	> 0	> 0
(i)[a]	$K_t - D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i)) - \nu\bar{K}(F(\nu(\kappa_d + \delta)) - F(f'(K_i)))$	$\gtreqless 0$	> 0
(j)	$(1-\nu)(K_t - D((1-\nu)(\kappa_c + \delta) + r_f + f'(K_i))) - \nu K_t$	< 0	> 0 if $\nu < 0.5$

[a] In case (i), ΔE can be positive or negative depending on the value of K_t and δ. For a given δ, there exist a threshold $\hat{K}_t$, such that for $K_t < \hat{K}_t$, $\Delta E < 0$, otherwise > 0.

References

Abrell, J., & Rausch, S. (2016). Cross-country electricity trade, renewable energy and european transmission infrastructure policy. *Journal of Environmental Economics and Management*, *79*, 87–113.

ACER. (2015). On unit investment cost indicators and corresponding reference values for electricity and gas infrastructure.

ACER. (2018). Study on the estimation of the value of lost load of electricity supply in europe.

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

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

Antweiler, W. (2016). Cross-border trade in electricity. *Journal of International Economics*, *101*, 42–51.

Antweiler, W., Copeland, B. R., & Taylor, M. S. (2001). Is free trade good for the environment? *The American Economic Review*, *91*(4), 877–908.

Auray, S., Caponi, V., & Ravel, B. (2018). *Price elasticity of electricity demand in france.*

Bahar, H., & Sauvage, J. (2013). Cross-border trade in electricity and the development of renewables-based electric power. *OECD Trade and Environment Working Papers, No. 2013/02*.

Bird, L., Lew, D., Milligan, M., Carlini, E. M., Estanqueiro, A., Flynn, D., … Orths, A. et al. (2016). Wind and solar energy curtailment: A review of international experience. *Renewable and Sustainable Energy Reviews*, *65*, 577–586.

Burke, P. J., & Abayasekara, A. (2018). The price elasticity of electricity demand in the united states: A three-dimensional analysis. *The Energy Journal*, *39*(2).

Chang, B., Kang, S. J., & Jung, T. Y. (2019). Price and output elasticities of energy demand for industrial sectors in oecd countries. *Sustainability*, *11*(6), 1786.

Copeland, B. R., & Taylor, M. S. (1994). North-south trade and the environment. *Quarterly Journal of Economics*, *109*(3), 755–787.

Copeland, B. R., & Taylor, M. S. (2004). Trade, growth, and the environment. *Journal of Economic Literature*, *42*(1), 7–71.

Cullen, J. (2013). Measuring the environmental benefits of wind-generated electricity. *American Economic Journal: Economic Policy*, *5*(4), 107–33.

Curtis, J., Di Cosmo, V., & Deane, P. (2014). Climate policy, interconnection and carbon leakage: The effect of unilateral UK policy on electricity and GHG emissions in Ireland. *Economics of Energy & Environmental Policy*, *3*(2), 145–158.

Dalla Longa, F., Kober, T., Badger, J., Volker, P., Hoyer-Klick, C., Hidalgo, I., … Zucker, A. (2018). Wind potentials for eu and neighbouring countries: Input datasets for the JRC-EU-TIMES model. *EUR 29083 EN*.

ENTSO-E. (2015). ENTSO-E guideline for cost benefit analysis of grid development projects.

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

Executive Order No. 12,866. (2016). *Current technical support document: Technical update to the social cost of carbon for regulatory impact analysis under Executive Order 12866*.

Fabra, N., & Llobet, G. (2019). Auctions with unknown capacities: Understanding competition among renewables. *Working paper*.

Golden, R., & Paulos, B. (2015). Curtailment of renewable energy in California and beyond. *The Electricity Journal*, *28*(6), 36–50.

Gowrisankaran, G., Reynolds, S. S., & Samano, M. (2016). Intermittency and the value of renewable energy. *Journal of Political Economy*, *124*(4), 1187–1234.

Hauch, J. (2003). Electricity trade and CO_2 emission reductions in the Nordic countries. *Energy Economics*, *25*(5), 509–526.

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

IEA. (2015). *Projected costs of generating electricity 2015 edition*. International Energy Agency.

IEA. (2018). *Renewables 2018: Analysis and forecasts to 2023*. International Energy Agency.

Joskow, P., & Tirole, J. (2000). Transmission rights and market power on electric power networks. *Rand Journal of Economics*, 450–487.

Joskow, P., & Tirole, J. (2005). Merchant transmission investment. *Journal of Industrial Economics*, *53*(2), 233–264.

Kakhbod, A., Ozdaglar, A. E., & Schneider, I. (2019). Selling wind. *SSRN Working Papers, No. 3304189*.

LaRiviere, J., & Lu, X. (2018). Transmission constraints, intermittent renewables and welfare. *Working paper*.

Lazkano, I., Nøstbakken, L., & Pelli, M. (2017). From fossil fuels to renewables: The role of electricity storage. *European Economic Review*, *99*, 113–129.

Loisel, R., Mercier, A., Gatzen, C., Elms, N., & Petric, H. (2010). Valuation framework for large scale electricity storage in a case with wind curtailment. *Energy Policy*, *38*(11), 7323–7337.

Luo, G., Li, Y., Tang, W., & Wei, X. (2016). Wind curtailment of China's wind power operation: Evolution, causes and solutions. *Renewable and Sustainable Energy Reviews*, *53*, 1190–1201.

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

Managi, S., Hibiki, A., & Tsurumi, T. (2009). Does trade openness improve environmental quality? *Journal of Environmental Economics and Management*, *58*(3), 346–363.

Mano, S., Ovgor, B., Samadov, Z., Pudlik, M., Jülch, V., Sokolov, D., & Yoon, J. Y. (2014). Gobitec and Asian super grid for renewable energies in Northeast Asia. *Spotinov print Ltd*.

Moura, P. S., & De Almeida, A. T. (2010). The role of demand-side management in the grid integration of wind power. *Applied Energy*, *87*(8), 2581–2588.

Reguant, M. (2019). The efficiency and sectoral distributional impacts of large-scale renewable energy policies. *Journal of the Association of Environmental and Resource Economists*, *6*(S1), S129–S168.

Schlömer, S., Bruckner, T., Fulton, L., Hertwich, e., McKinnon, A., Perczyk, D., … Wiser, R. (2014). Annex III: Technology-specific cost and performance parameters. *Climate Change 2014: Mitigation of Climate Change*.

Sensfuß, F., Ragwitz, M., & Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy policy*, *36*(8), 3086–3094.

Suberu, M. Y., Mustafa, M. W., & Bashir, N. (2014). Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renewable and Sustainable Energy Reviews*, *35*, 499–514.

TYNDP. (2016). 10-year network development plan.

Von Der Fehr, N.-H. M., & Sandsbråten, L. (1997). Water on fire: Gains from electricity trade. *Scandinavian Journal of Economics*, *99*(2), 281–297.

Williamson, O. E. (1966). Peak-load pricing and optimal capacity under indivisibility constraints. *The American Economic Review*, *56*(4), 810–827.

World Trade Organization, & United Nations Envrionmental Protection. (2009). *Trade and climate change*. World Trade Organization.