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WORKING PAPER

Implementing a CO_2 price floor in the electricity sector: analysis of two interconnected markets

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The debate on the possible reforms of the EU ETS market is still underway. One of the measures actually considered is an eventual price floor that would avoid the price to hit very low values. This regulation instrument is implemented in other market for permits, as in California. We contribute to the recent literature on the carbon price floor (CPF) by analyzing its effect on the electricity sector in two interconnected countries. We characterize production and carbon market equilibria under symmetric and asymmetric regulation and simulate our results for the French and German electricity markets. The simulation allows to illustrate and calculate the likely impact of CPF measures, which can have counterintuitive effects on the carbon price.

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1. Introduction

The basic concept of a combined system of price ceilings and floors in allowance trading goes back to Roberts and Spence (1976). Several emissions trading systems, including the Regional Greenhouse Gas Initiative (RGGI) and those in California and Quebec as part of the Western Climate Initiative, have adopted price floors for allowances in the form of an auction reserve price, that is, the regulator sets an auction price (reserve price) level below which no allowances will be sold. Allowances left unsold when the auction reserve price was not met have usually been invalidated later. The carbon price floor (CPF henceforth) thus allows market confidence and support in times of unexpected economic shocks and it prevents price to decrease when other environmental policies, as subsidies to renewables, put downward pressure on carbon prices. In the long term, price floors can enhance long-term investment certainty by providing a clearer signal of regulators' commitment to implement policy that is in line with ambitious decarbonization targets and is directly translatable into private and public investment decision calculations. Price floors may also help avoid myopic price formation if they align the carbon price trajectory more closely with the efficient level (Wood and Jotzo, 2011).

In Europe, the EU ETS is the main component of the climate change policy. The European market for pollution permits has now a long history, with flaws and reforms, like the Market Stability Reserve, introduced in 2019, to realign supply and demand in order to sustain prices.[1] However, despite the reserve stability mechanisms, the EU ETS still suffers from three major problems (Palhe et al., 2018; Perino et al., 2019; Perino et al., 2021). First, the short-term time horizon of traders prevents the formation of a market price that reflects the scarcity of allowance supply in the long term. Second, the allowance market reacts in a very sensitive way to climate policy announcements in the EU that are interpreted as cues regarding the future stringency of the cap. Empirical research suggests that the allowance price is thus pushed below the level that would be necessary for cost-efficient decarbonization. Third, all additional climate mitigation policies in EU ETS member states dampen the price as long as the corresponding allowances are not permanently deleted. There is still room to further improvements of the system, like the introduction of a CPF.

[1] A synthetic view of the EU ETS history and development can be found at https://fsr.eui.eu/eu-emission-trading-system-eu-ets/. Much has been written on the European Allowance market, but summarizing that literature is beyond the scope of this paper. For a global assessment of the market, the reader can refer to "2021 State of the EU ETS report" (2021), available at https://ercst.org/publication-2021-state-of-the-eu-ets-report/.

Member States can already decide to nationally include other CO_2 price instruments besides the European carbon market. For instance, a price floor implementation option has already been introduced by the UK (Hirst, 2018) before the Brexit. The UK CPF requires power sector facilities covered by the EU ETS to pay a carbon price support that scales with EUA prices to ensure that a specific domestic minimum carbon price is always achieved. More recently, supportive signals have also come from the Netherlands (ICAP, 2017), where a carbon price floor was to be set at €12.30/tCO_2 in 2020, and then progressively increase to €31.90 by 2030, Sweden (Stam, 2018; Makkonen et al., 2019), and Portugal and Spain (Brnic and Thévoz, 2018). In recent years, France was the only EU member state openly advancing the idea of a price floor (Szabo, 2016). Like the UK CPF, the French initiative envisioned a price floor only for the power sector.[2] German discussions about the carbon price floor option (Edenhofer et al., 2017), with 11 member state governments asking the federal government to consider the introduction of an EU ETS price floor (Demirdag, 2018), can trigger support to this policy measure at the EU level. According to Flachsland et al. (2020) "*a minimum price should be introduced in the EU ETS, ideally EU-wide or in a coalition of countries but, if necessary, unilaterally by Germany*." The 2021 year will be decisive for Europe's climate policy, with a wide range of new legislation promised to align current EU climate and energy policies with a new emissions reduction target of 55% by 2030, in the context of the Green deal. This reform can potentially redesign the EU ETS. In particular, "*one tool currently missing from the European Green Deal arsenal is a carbon price floor, which can set a minimum carbon pricing in both ETS and non-ETS sectors. After years of discussions, the time for its introduction might now have come*." (Demertzis and Tagliapietra, 2021). Newbery et al. (2019) recommend a CPF designed as a carbon levy to "top up" the European Emission Allowances (EUA) price to €25–30/tCO_2, rising at 3–5% annually above the rate of inflation, at least until 2030.

Supplementary policy measures such as support to renewables, in particular if applied to specific sectors, are not effective owing to the "waterbed effect" (Perino, 2018) that occurs under the existing CO_2 ceiling of the EU ETS allowances. CO_2 emissions that firms reduce by an additional policy instrument may lead to additional CO_2 emissions elsewhere in the European economy. This waterbed effect occurs because under an emissions cap, reductions at one source do not prevent emissions increases at another source.

More specifically, the waterbed effect can occur in three different ways that are related to one another (Burtraw et al., 2018). First, the direct waterbed effect consists of relocation of activities, in that emissions from one location decrease, while they increase at another location. The indirect waterbed effect is a negative effect on the price of

[2] https://www.euractiv.com/section/emissions-trading-scheme/news/france-calls-for-carbon-price-floor-to-counter-oil-crash/

emission allowances that indirectly results in an increase in emissions from other installations under the EU ETS. Finally, a dynamic waterbed effect can arise, via emissions that are currently unused may be used at a later stage (Perino, 2018). This might also introduce some counterintuitive effects, like increase in emission, when supplementary policy measures interact with the MSR (Rosendhal, 2019).

If a price floor is introduced in a market for permits, policymakers need to take permits out of the market to keep the price from falling below the floor. But if firms' voluntary abatement reduces permit demand, this increases the number of permits that have to be taken out of the market. If the price floor is accompanied by the cancellation of allowances (Perino, 2019; Hintermayer, 2020), this measure can solve the EU ETS flaws analyzed by Palhe et al. (2017).

Which would be the impact of a price floor on the electricity sector? According to Newbery et al. (2019) "*For electricity generation, a carbon price plays two distinct roles. In the short run, it affects emissions from existing plant; in the longer run, it guides the choice of plant to install and retire. The short-run impact raises more strongly the variable cost of plant with higher carbon intensities; hence it substitutes via the merit order from higher- to lower-carbon intensive plant, thus immediately reducing emissions.*" Our model tackles this issue, by investigating the cases under which the price floor increases the variable costs of polluting generation, when two interconnected electricity markets are concerned. We thus investigate whether a price floor creates a waterbed effect (direct or indirect) that could constrain emission reductions in the electricity sector, in a short-term perspective. We argue that the characteristics of the electricity market, i.e. the production of an homogenous good by different technologies with different carbon emission rates and costs, as well as transport constraints, may interact with a floor on the CO_2 emission markets. This interaction leads to some cases where the CPF does not prevent the carbon price to decrease. To better illustrate our result, we resort to a numerical simulation model, calibrated on the French and German electricity markets. This application is quite natural, as these two countries supported a CPF design, on one side, and have interconnected electricity markets, yet characterized by a very different mix, on the other. To the best of our knowledge, we are the first to propose an analytical model able to detail the consequences on electricity markets of a sectorial carbon price floor, both in the case of two countries agreeing to put a CPF or in an asymmetric configuration where only one country implement it.[3]

The paper is organized as follows. Section 2 describes a "one-period" model to highlight 1) the existence of discontinuity in CO_2 emissions demand for the electricity sector, 2) the possibility of waterbed effect with the

[3] A qualitative analysis of the waterbed effect in Germany can be found at https://www.cleanenergywire.org/factsheets/national-climate-measures-and-european-emission-trading-assessing-waterbed-effect

implementation of price floor on the emissions market and 3) the possible increase of CO_2 emissions demand when the price floor is not imposed on the CO_2 market (therefore all countries) but on certain countries participating in the market (asymmetric regulation). The effect on the equilibrium price of the CO_2 market of a CPF is either zero or negative (i.e. a price decrease). It can also be positive when the price floor is asymmetrical. No time step is mentioned in section 2, even if the demand for electricity varies depending on the time of day, the day of the week and the time of year. However, the emissions compliance period is not hourly. As a consequence, it is necessary to consider a multi-period model. Assuming annual compliance, the ideal would be to consider a model of 8760 periods (hours). As solving this type of model analytically is tedious, in section 3 we switch to a numerical calibration of the French and German electricity markets, using 2018 hourly data. We thus illustrate the analytical results obtained in section 2. The configurations under which the carbon price floor delivers the expected results or creates the waterbed effect are detailed, under unilateral or bilateral CPF. Section 4 concludes.

2. The model

This section describes the one-period model[4] used. Given the variability of electricity demand (hourly, daily, monthly), the period considered is one hour. Consequently, this model focuses on the impact in the short-term of a CPF on electricity production and on demands of CO_2 emissions permits. Without loss of generality, assuming that the emissions compliance period is hourly,[5] the impact of this regulation on the equilibrium price on the CO_2 market can be determined.

2.1. Assumptions and notation

There are C interconnected countries $(c = 1, \cdots, C)$. The available interconnection capacities between two countries (c and c') are $T_{c \to c'}$.[6] The electricity demand of c is D_c. To satisfy the electricity demands, each country has N production technologies $(n = 1, \cdots, N)$. The available production capacity of technology n in country c is $K_{c,n}$. For each technology n, we denote by r_n the efficiency level, p_n the fuel price, e_n the CO_2 emission factor and $x_{n,c \to c'}$ the energy produced by technology n in country c for country c'. The CO_2 market price is σ and the total volume of emissions is limited by the allocation A whose amount is decided and auctioned by a regulator. The notations used are listed in Table 1 for given country c.

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[4] The structure of this relatively simple model is easily adaptable to several periods.
[5] Admittedly, in reality the emissions compliance period is annual, but the effects observed in this section are observed in section 3 when the 8760 hours of the year are considered.
[6] We consider commercial capacities, therefore it is possible that $T_{c \to c'} \neq T_{c' \to c}$.

Given the above notations, the short-run marginal cost of generation and pollution of technology n, function of CO_2 price, is

$$mc_n(\sigma) = \frac{p_n}{r_n} + \sigma e_n. \tag{1}$$

D_c	Demand of *c*
$T_{c\to c'}$	Transport capacity to trade in electricity between *c* and *c'*
$K_{c,n}$:	Available production capacity of technology *n* in country *c*
r_n:	Efficiency level of *n*
p_n	Fuel cost of *n*
e_n:	CO2 emission factor of *n*
$x_{n,c\to c'}$	Energy produced by technology n in country *c* for country *c'*
A	Total volume of emissions allocation
σ	CO_2 market price

Table 1. Notation

2.2. Optimization

We take a normative perspective. Under perfect competition, the welfare maximizing objective is to satisfy electricity demands D_c at the lowest cost, subject to the production and interconnection capacity constraints (merit order).[7]

The objective function is:

$$\sum_{n=1}^{N} \sum_{c'=1}^{C} \sum_{c=1}^{C} mc_n(\sigma) \times x_{n,c\to c'} \,. \tag{2}$$

Equilibrium on electricity markets.

- The electricity supplied by all existing plants for *c* is equal to the demand of *c*:

$$\sum_n x_{n,c'\to c} = D_c \qquad \forall c, c'. \tag{3}$$

- Electricity trade between countries are limited:

$$\sum_n x_{n,c'\to c} \le T_{c'\to c} \quad \forall c' \ne c. \tag{4}$$

- Electricity supplied must respect the following capacity constraints:

$$\sum_{c'} x_{n,c\to c'} \le K_{c,n} \;\; \forall c, n. \tag{5}$$

Equilibrium condition on the CO_2 market (compliance). Each country must cover pollution in a perfectly competitive permits' market. A country c can buy at a price σ per unit z_c permits. In this one-period model there is neither banking nor borrowing,

$$z_c = \sum_{c'=1}^{C} \sum_{n=1}^{N} e_n \times x_{n,c\to c'} \quad \forall c \tag{6}$$

and

$$\sum_{c=1}^{C} z_c \le A. \tag{7}$$

[7] The merit order is a rank of available electrical generation based on ascending order of marginal costs.

Solving the problem. As in Chaton et al. (2015), the problem is solved in two stages. In the first step, for a given (exogenous) σ, we solve the electricity market equilibrium, then in the second step we calculate the CO_2 market equilibrium.

2.2.1. Equilibrium on the electricity markets at a given CO_2 price

Before calculating the equilibrium in the electricity market, it is worthwhile to introduce the following definition and notations.

Definition 1 *Where the marginal fuel cost of technology n' is lower than that of technology n i.e.* $\frac{p_{n'}}{r_{n'}} \leq \frac{p_n}{r_n}$ *we define* $\sigma_{n',n} = \frac{1}{e_{n'}-e_n}\left(\frac{p_n}{r_n} - \frac{p_{n'}}{r_{n'}}\right)$ *the* CO_2 *fuel switching price from n' technology to n technology i.e.* $\forall\sigma < \sigma_{n',n}$ *the short-run marginal cost of generation and pollution of technology n'* ($mc_{n'}$) *is lower than technology n's* (mc_n): $mc_{n'}(\sigma) < mc_n(\sigma)$ *and* $\forall\sigma \geq \sigma_{n',n}$, *we have* $mc_{n'} \geq mc_n$.[8]

Remark 1 *If* $e_n = e_{n'}$ *then* $\sigma_{n,n'}$ *does not exist.*

Notation *If* $e_n = e_{n'}$ *we set* $\sigma_{n',n} = -1$, *as a result we have* $\frac{N(N-2)}{2}$ CO_2 *fuel switching prices.*

For all carbon-free renewable energy technology, the marginal cost $mc_n(\sigma)$ is zero. As we consider only one-period model, these technologies are ranked first in the merit order. To avoid confusion, we refer to demand as net of these technologies. Let $\overline{N}$ be the number of technologies that are not carbon-free renewable technologies. It is possible to rank in ascending order the CO_2 fuel switching prices. The rank of a technology in the merit order depends on this order and the CO_2 price.[9]

Remark 2 *If* $\sigma = 0$ *the ranking is done in increasing order of the marginal fuel costs,* $\frac{p_n}{r_n}$.

Remark 3 *If* $e_n = e_{n'}$ *and* $p_n/r_n < p_{n'}/r_{n'}$ *the technology n' will always be after the technology n in the merit order. It will be just after n if and only if there is no* CO_2 *fuel switching price between* $[\sigma_{k,n}; \sigma_{n',l}]$ *and* $\sigma < \sigma_{n',l}$. *The same would is true if* $\frac{p_{n'}}{r_{n'}} > \frac{p_n}{r_n}$ *and* $e_{n'} > e_n$ *i.e.* $\sigma_{n',n} < 0$.

Assumption 1 *At the equilibrium, when the* CO_2 *market price is different from a* CO_2 *fuel switching price, we assume, in this section***,** *that, for a given technology (same marginal cost of production and pollution), a country first uses these production capacities before those of other countries (with the neighboring countries first).*

Proposition 1 *When the* CO_2 *market price is different from a* CO_2 *fuel switching price (i.e. if assumption 1 is not verified) then there may be several cost minimization solutions to satisfy electricity demands.*

To illustrate Proposition 1, consider demands such that there are at least two countries where the marginal technology is the same and is not operating at full capacity and the interconnection between these two countries is not saturated. If *x* MWh of this technology is needed to satisfy these demands, then any linear combination of the

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[8] If $\frac{p_n}{r_n} > \frac{p_{n'}}{r_{n'}}$ and $e_n > e_{n'}$ then $\sigma_{n',n} < 0$ and for all $\sigma \geq 0$, $mc_n > mc_{n'}$.

[9] For example, if there are 3 production technologies (i, j, k) such as $0 < \sigma_{i,j} < \sigma_{i,k} < \sigma_{j,k}$ then if $\sigma < \sigma_{i,j}$ the merit order is i, j, k i.e. the technology *i* is used first, then *j* and finally *k*. If $\sigma_{i,j} < \sigma < \sigma_{i,k}$ the merit order is *j*, *i*, *k*; if $\sigma_{i,k} < \sigma < \sigma_{j,k}$ the merit order is *j*, *k*, *i*, and if $\sigma > \sigma_{j,k}$ the merit order is *k*, *j and i*.

production of this technology in each country that produces x and satisfies the capacity constraints of production and interconnection is optimal.

We can rename the technologies according to their rank in the merit order (as a function of the CO_2 price)[10]: thus when the CO_2 price is σ, we write $j = 1_\sigma$ the first technology used, $j = 2_\sigma$ the second technology that will be used if the capacities of the first are not sufficient and so on. Consequently, $x_{\mathrm{j}=\mathrm{l}_\sigma,c\to c}$ (respectively $x_{\mathrm{j}=\mathrm{l},c\to c'}$) represents the production in country c of the technology with the rank l in the merit order when the CO_2 price is σ for its consumption (resp. for exports to country c'). Under Assumption 1, if $x_{\mathrm{j}=\mathrm{l}_\sigma,c\to c'} > 0$ then for all j we have $x_{\mathrm{j},c'\to c} = 0$.

Case 1. The CO_2 price is not equal to a CO_2 fuel switching price.

Proposition 2 *If for all n and n', $\sigma_{n,n'} \neq \sigma$, for all c the equilibrium productions are*

$$x^*_{j=1_\sigma,c\to c} = \min\left(D_c, K_{j=1_\sigma,c}\right), \tag{8}$$

$$x^*_{j=1_\sigma,c\to c'} = \min\left(T_{c\to c'}, \max\left(D_{c'} - K_{j=1_\sigma,c'}, 0\right), \max\left(K_{j=1_\sigma,c} - D_c, 0\right)\right), \forall c' \neq c, \tag{9}$$

and $\forall l_\sigma \in \{2, \cdots, \overline{N}\}$:

$$x^*_{j=l_\sigma,c\to c} = \min\left(\max\left(D_c - \sum_{j=1_\sigma}^{l_\sigma-1} \sum_{c'} x_{j,c'\to c}, 0\right), K_{j=l_\sigma,c}\right) \tag{10}$$

and $\forall c' \neq c$

$$x^*_{j=l_\sigma,c\to c'} = \min\left(Td_{c\to c'}, \max\left(D_{c'} - \sum_{j=1_\sigma}^{l_\sigma} K_{j,c'} - \sum_{j=1_\sigma}^{l_\sigma-1} x_{j,c\to c'}, 0\right), \max\left(\sum_{j=1_\sigma}^{l_\sigma} K_{j,c'} - D_{c'}, 0\right)\right), \tag{11}$$

where

$$Td_{c\to c'} = \max\left(T_{c\to c'} - \sum_{j=1_\sigma}^{l_\sigma-1} x_{j,c\to c'}, 0\right). \tag{12}$$

Case 2. The CO_2 price is equal to a CO_2 fuel switching price.

Let $X^*_{-n,c}(\sigma)$ be the production for the country c of all technologies ranked before n in the merit order when the CO_2 price is σ i.e. if the technology n is classified at rank l,

$$X^*_{-n,c}(\sigma) = \sum_{c'=1}^{C} \sum_{j=1_\sigma}^{l_\sigma-1} x^*_{j,c'\to c'} \tag{13}$$

and $D_{-n,c}(\sigma)$ be the remaining demand of c addressed to n

$$D_{-n,c}(\sigma) = D_c - X^*_{-n,c}(\sigma). \tag{14}$$

Proposition 3 *Then if $\sigma = \sigma_{n,k}$, there exists a unique equilibrium of production if and only if for all* c, *$K_{n,c} + K_{k,c} \leq D_{-n,c}(\sigma_{n,k})$. Otherwise, if there is a country c such $D_{-n,c}(\sigma_{n,k}) < K_{n,c} + K_{k,c}$ there are several supply equilibria. Indeed, all the productions $x^*_{n,c\to c}$ and $x^*_{k,c\to c}$ which verify $x^*_{n,c\to c} + x^*_{k,c\to c} = D_{-n,c}(\sigma_{n,k})$ such as $x^*_{n,c\to c} \in [0, K_{n,c}]$ and $x^*_{k,c\to c} \in [0, K_{k,c}]$ are supply equilibria. Then, for all c such as $D_{-n,c}(\sigma_{n,k}) < K_{n,c} + K_{k,c}$ at the equilibrium the quantities produced by k and n for c satisfy*

[10] The l[th] technology in merit order ($j = l$) depends on σ. The order remains the same when σ is between two consecutive CO_2 fuel switching price.

$$x^*_{j=l_{\sigma_{n,k}},c\to c} = x^*_{n,c\to c} = \min\left(D_{-n,c}(\sigma_{n,k}), K_{n,c}\right) - \alpha_c(\sigma_{n,k}), \quad (15)$$

and

$$x^*_{j=l_{\sigma_{n,k}}+1,c\to c} = x^*_{k,c\to c} = D_{-n,c} - \min\left(D_{-n,c}(\sigma_{n,k}), K_{n,c}\right) + \alpha_c(\sigma_{n,k}), \quad (16)$$

where

$$\alpha_c(\sigma_{n,k}) \in \left[0; \min\left(D_{-n,c}(\sigma_{n,k}), K_{n,c}\right) + \min\left(D_{-n,c}(\sigma_{n,k}), K_{k,c}\right) - D_{-n,c}(\sigma_{n,k})\right]. \quad (17)$$

The supply equilibrium of other technologies verifies (8)-(12).

Case 3. The CO_2 price is equal to zero.

Proposition 4 *If there are two technologies k and n such that* $\frac{p_n}{r_n} = \frac{p_k}{r_k}$ *and if there is a country c such* $D_{-n,c}(0) < K_{n,c} + K_{k,c}$ *then several equilibrium productions exist. At equilibrium the quantities produced by k and n for c satisfy equations similar to* (15) - (17)*, indeed if the technology n (resp. k) is classified at rank l (resp. l*+1*)*

$$x^*_{j=l,c\to c} = x^*_{n,c\to c} = \min\left(D_{-n,c}(0), K_{n,c}\right) - \alpha_{c,n,k}(0), \quad (18)$$

and

$$x^*_{j=l+1,c\to c} = x^*_{k,c\to c} = D_{-n,c} - \min\left(D_{-n,c}(0), K_{n,c}\right) + \alpha_{c,n,k}(0), \quad (19)$$

where

$$\alpha_{c,n,k}(0) \in \left[0; \min\left(D_{-n,c}(0), K_{n,c}\right) + \min\left(D_{-n,c}(0), K_{k,c}\right) - D_{-n,c}(0)\right]. \quad (20)$$

The equilibrium productions of other technologies verify (8)-(12).

There can obviously be more than two technologies for which the marginal production $\left(\frac{p_n}{r_n}\right)$ costs are equal.

Assumption 2 *Thereafter, we assume that for all n and k such as* $\frac{p_n}{r_n} = \frac{p_k}{r_k}$ *we have* $e_n \neq e_k$*. Then, for a unique supply equilibrium to exist when* $\sigma = 0$*, we assume that the merit order for technologies that have the same marginal production costs is established in ascending order of emission factors.*

2.2.2. Equilibrium in the CO_2 market

For a given CO_2 price, the emissions of country *c* defined by (6) becomes

$$z_c(\sigma) = \sum_{j=1_\sigma}^{\overline{N}_\sigma} e_j \sum_{c'=1}^{C} x^*_{j,c\to c'}, \quad (21)$$

and the equilibrium condition on the CO_2 market is

$$\sum_{c=1}^{C} z_c(\sigma) \leq A. \quad (22)$$

Let Γ be the number of CO_2 fuel switching prices strictly positive. Let σ_1 be the smallest positive CO_2 fuel switching price, σ_2 the second smallest positive CO_2 fuel switching price and so on until σ_Γ the highest.

CO_2 emission permit demand function. For all i ($i = 1, \cdots \Gamma$), under Assumption 1 the CO_2 emission permit demands $z_c(\sigma)$ are constants over each interval $]\sigma_{i-1}; \sigma_i[$ where $\sigma_0 = 0$, insofar as the merit order in these intervals are the same. Hence, for all i ($i = 1, \cdots \Gamma$), $\forall \sigma \in]\sigma_{i-1}; \sigma_i[$, $z_c(\sigma) = z_c(\sigma_{i-1})$. When the CO_2 price is equal to a CO_2 fuel switch price i.e. $\sigma = \sigma_i$, there may be several supply equilibria (case 2 above). The resulting CO_2 emissions permit demand may be different, more precisely, if $\sigma = \sigma_i$ the demand for CO_2 emissions permit of *c* is between $[z_c(\sigma_i); z_c(\sigma_{i-1})]$. This configuration leads to the following:

Proposition 5 *CO_2 emission permit demand functions $z_c(\sigma)$ are continuous and are step functions, but not necessarily decreasing.*

Indeed, as national production capacities are different and trade is possible, a country's demand for emission permits may increase with the increase in the price of CO2 (even under Assumption 1). In contrast, the total demand for CO_2 emission permits is a decreasing function of permit prices.

Let A_i be the minimum of the emissions of the production equilibria when the price is σ_i $(i = 0,1,\cdots,\Gamma)$, i.e. $A_i = \sum_{c=1}^{C} z_c(\sigma_i)$ then $A_{i+1} > A_{i-1}$ $(i = 1,\cdots,\Gamma - 1)$.

The equilibrium price on the CO_2 market, σ^* depends on the amount of CO_2 emission permits (A).

Proposition 6 *There are $(\Gamma + 1)$ possible equilibrium CO_2 prices $\sigma^* \in \{0;\ \sigma_1;\sigma_2;\cdots;\sigma_\Gamma\}$. So, the equilibrium price in the market for CO_2 is:*

$$\sigma^* = \begin{cases} 0 & if\ A \geq A_0 \\ \sigma_1 & if\ A \in [A_1; A_0[\\ \vdots & \vdots \\ \sigma_\Gamma & if\ A \in [A_\Gamma; A_{\Gamma-1}[\end{cases} \tag{23}$$

Remark 4 *If $A < A_\Gamma$ the program defined by equations (2) – (7) has no solution.*

2.3. Introducing a price floor

In this sub-section, the impact of a price floor, $\underline{\sigma}$, imposed on all countries i.e. on the CO_2 market (symmetrical regulation) and that of different national price floors (asymmetrical regulation) are studied.

2.3.1. On CO_2 emissions permits demands

Symmetrical regulation. When a CPF, $\underline{\sigma}$ is imposed on all countries, it will only be effective if the market price of CO_2, σ is lower than $\underline{\sigma}$, otherwise it will have no impact.

Notice that if $\underline{\sigma} \leq \sigma_1$ (the smallest positive CO_2 fuel switching price) the CPF will not impact the total demand for CO_2 emissions permits and therefore on the CO_2 equilibrium price. When $\underline{\sigma} > \sigma_1$ is effective, the merit order is that obtained for a CO_2 price equal to $\underline{\sigma}$.

Proposition 7 *If there is no technology n' as for any other technology n, the following inequalities are verified $\frac{p_{n'}}{r_{n'}} > \frac{p_n}{r_n}$ and $e_{n'} > e_n$ i.e. $\nexists \sigma_{n',n} < 0$ then whatever the CPF is, it will never lead to an increase in the demand of CO_2 emission permits (for a given CO_2 price). The demand for emission permits may decrease (with or without waterbed effect).*

Asymmetrical regulation. In this case, i.e. if some countries are not subject to the CPF, we show that it is possible that following the introduction of a CPF the total demand for CO_2 emission permits may increase (see the example in the Appendix A.1. and the numerical application in Section 3).

Theorem 1 *If there is at least one technology n' such as for any other technology n, $\frac{p_{n'}}{r_{n'}} > \frac{p_n}{r_n}$ and $e_{n'} > e_n$ then an unilateral CPF may generate an increase in total CO_2 emissions permits demand.*

This increase in permits demand occurs when the capacity of the least expensive technologies is saturated, and the interconnection is not saturated when the technology *n'* is not in use.

More generally, if for the same technology the production costs of the countries are identical (this is not the case in reality), if the CPF is imposed on all the countries, then if there is an impact on the emissions these will decrease. If the regulation is asymmetric, i.e. the CPF is imposed on some countries but not all countries then demand of CO_2 emissions permit may increase.

Thus, let's assume that when trade is not possible and a CPF in country P leads to the replacement of part of the production of technology b (which worked without a price floor) $\alpha q_{P,b}$ by technology a with $e_a < e_b$ so $\underline{\sigma} > \sigma_{ba}$. In this case, emissions are reduced by $(e_a - e_b)\alpha q_{P,b}$.

A CPF alters the relative competitivity of the different production technologies, in particular if the measure is asymmetric. A CPF in fact modifies the merit order, and the result in the equilibrium will crucially depend on the transmission capacity between the two trading countries. This shift, in turn, has consequences on the countries' emissions, that can increase or decrease, depending on the electricity mix and the costs associated to it.[11]

2.3.2. On the CO_2 equilibrium price

Symmetric regulation. The decrease in demand for CO_2 emission permits, noted Δ_E^- following the introduction of a CPF in all countries may lead to a decrease in CO_2 price. To remedy this price decrease, it is sufficient to reduce the supply of permits by Δ_E^-.

Asymmetric regulation. Asymmetric regulation can generate a comparative advantage for countries not subject to the CPF. If the CPF, $\underline{\sigma}$, is higher than the CO_2 market price, σ, then a new CO_2 fuel switch price can be defined, noted $\sigma_{n,n'}(\underline{\sigma})$ and subsequently named "*Country CO_2 fuel switch price*". Thus, let us *n'* a production technology from the country where the CPF is imposed and *n* a production technology from the country where there is no price floor, then if σ is lower $\underline{\sigma}$ than[12]

$$\sigma_{n,n'}(\underline{\sigma}) = \frac{1}{e_n}\left(\frac{p_{n'}}{r_{n'}} + \underline{\sigma} e_{n'} - \frac{p_n}{r_n}\right). \tag{24}$$

[11] More precisely, if trading is possible and there is a technology c in the country P' such that $\frac{p_c}{r_c} + \boldsymbol{\sigma e_c} < \frac{p_a}{r_a} + \underline{\boldsymbol{\sigma}}\boldsymbol{e}_a$; $\frac{p_c}{r_c} + \boldsymbol{\sigma e_c} < \frac{p_b}{r_b} + \boldsymbol{\sigma e_b}$ and $\boldsymbol{e_c} > \boldsymbol{e_b}$ and such as the capacity of technology b of P' not used for P' (noted $\widetilde{\boldsymbol{K}}_{\boldsymbol{P',b}}$) is less than $\min(\boldsymbol{\alpha q_{P,b}}; \widetilde{\boldsymbol{T}}_{\boldsymbol{P'\to P}})$ where $\widetilde{\boldsymbol{T}}_{\boldsymbol{P'\to P}}$ is the remaining possible exchange capacity between P' and P then global CO_2 emissions will increase by $(\boldsymbol{e_b} - \boldsymbol{e_c})\min(\boldsymbol{\alpha q_{P,b}}; \widetilde{\boldsymbol{T}}_{\boldsymbol{P'\to P}}) - (\boldsymbol{e_a} - \boldsymbol{e_b})\max(\boldsymbol{\alpha q_{P,b}} - \widetilde{\boldsymbol{T}}_{\boldsymbol{P'\to P}}; \boldsymbol{0})$. If this technology c does not exist, then emissions can decrease (with or without waterbed effect).

[12] Of course, if σ is greater than $\underline{\sigma}$, this fuel switch does not exist.

This means that for any CO_2 price below (respectively above) $\sigma_{n,n'}(\underline{\sigma})$ the technology n of the country without CPF will be more profitable (respectively less profitable) than the technology n' of the country with CPF.

Figures 1.a – 1.c illustrate the impact of a CPF on the market price of CO_2, $\underline{\sigma}$ such as $\sigma_1 < \underline{\sigma} \leq \sigma_2 + \epsilon$. Suppose that, depending on the price on the CO_2 market, the implementation of a CPF contributes to reducing the demand for emissions permits (if the market price is lower than σ_1), increasing them (if $\sigma_1 \leq \sigma \leq \sigma' < \sigma_2$). Obviously for any price on the CO_2 market higher than σ_2 the CPF will no longer be effective. Note that σ' corresponds to a "country CO_2 fuel switch price". Therefore, if the number of permits on the market A is such that $A2 < A < A1$, without a CPF the equilibrium price is σ_1 and with price floor the price is zero (see Figure 1.a). Consequently, one solution so that the equilibrium CO_2 price does not decrease following the introduction of the CPF is to reduce the number of permits placed on the market. In this example, this number must be between $A2$ and $A1$. If $A3 < A < A2$, with and without CPF the price is σ_1 (see Figure 1.b). If $A4 < A < A3$, without the CPF the CO_2 price is σ_1 and with the CPF the CO_2 price is $\sigma' > \sigma_1$ (see Figure 1.c). For any $A \leq A4$ the CO_2 market price without a CPF is equal to $\sigma_2 > \underline{\sigma}$.[13]

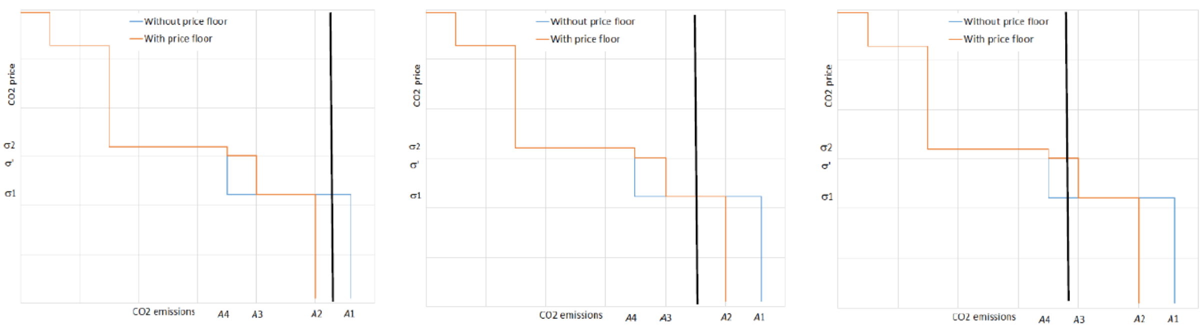


Figure 1.a Figure 1.b Figure 1.c

Interpretation: The step functions represent the inverse demand for global emission permits with and without CPF. Here, this CPF $\underline{\sigma}$ is such as $\sigma_1 < \underline{\sigma} \leq \sigma_2 + \epsilon$. The CO_2 permit supply is represented by a vertical line (the black lines). When the market price is less than σ1, then the CPF contributes to reducing the demand for CO_2 emission permits. Consequently, if the supply of permits A is between A2 and A1 (as in the figure 1.a), the introduction of the CPF contributes to bring down the price on the CO_2 market (in our example to 0).

Figure 1 Equilibrium on the CO2 market (depending on the supply of emission permits)

3. Annual compliance and hourly equilibria

We now generalize our model to a more realistic situation that is considering the horizon of annual compliance (as it is the case in the EU ETS), based on hourly demand over one year (that is 8760 hours and thus markets). As a consequence, loads, production, electricity trade variables become function of time denoted by t (t=hour): D_c becomes $D_c(t)$; $x_{n,c\to c'}$ is $x_{n,c\to c'}(t)$ and $T_{c\to c'}$ $T_{c\to c'}(t)$. We assume constant fuel prices over the year.

[13] Consequently, over this interval, the CO_2 floor price is not effective.

Equilibrium condition on the CO_2 market. We assume yearly compliance, without banking nor borrowing for simplicity. Equation (21) becomes now:

$$z_c(\sigma) = \sum_{t=1}^{8760} \sum_{j=1_\sigma}^{\overline{N}_\sigma} e_j \sum_{c'=1}^{C} x^*_{j,c\to c'}(t),$$

and the objective function is

- the variable costs of power supplied $\left(\sum_{c'} \sum_n \left(\sum_t mfc_n \times x_{n,c\to c'}(t)\right)\right)$ plus
- the emission cost $\sum_c \Theta_c \ \sum_{c'} \sum_n \left(\sum_t e_n \times x_{n,c\to c'}(t)\right)$

where mfc_n is the marginal fuel cost of *n* and

$$\Theta_c = \begin{cases} max(\sigma, \bar{\sigma}) & \text{if the country sets a price floor } \bar{\sigma} \\ \sigma & \text{otherwise.} \end{cases}$$

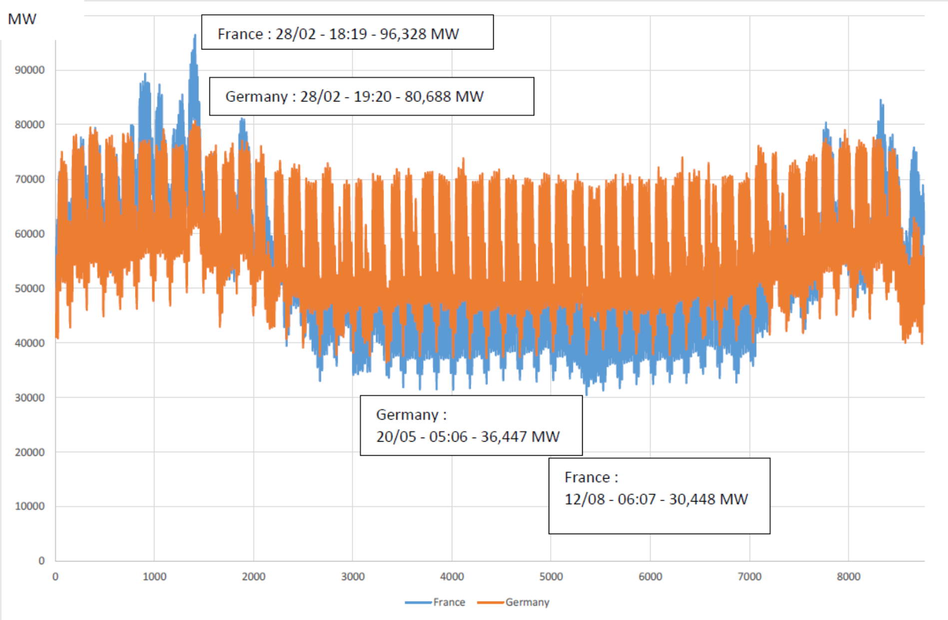
Hourly CO_2 price equilibria computation becomes tedious, so we switch to a case study with a numerical application to illustrate them.

3.1. Numerical application: France and Germany

We illustrate our model on the French and German electricity markets, the most developed ones in continental Europe. According to the BP statistical Review of World Energy[14], in 2018 they accounted for 37.3% of total EU electricity production (over a total of 648.7 TWh gross production, Germany covers 19.8%, France 17.5% followed by the UK 10.2% contribution). Moreover, these two countries present interesting features, such as different demand seasonality and electricity production mix. We use 2018 data.

Demand. We use load charges from the French transport operator, Réseau de transport d'électricité Français (RTE) and the European one (ENTSO-E). Hourly demand of each country is displayed by Figure 2. Residential[15] and service shares being higher in France than in Germany, demand seasonality is stronger in France. RTE (2018) also stresses that electricity demand for heating is quite high in France. Nowadays, average hourly consumption in France amounts to 54303 MWh whereas it reaches 59085 MWh in Germany.

[14] https://knoema.com/BPWES2017/bp-statistical-review-of-world-energy-main-indicators
[15] According to RTE (2018), the residential sector represents 35.7% of total electricity French consumption in 2017. Eurostat reports that 2017 electricity demand for heating needs was 38.7% in France and 21.5% in Germany.



Interpretation: Peak demand in 2018 observed on February 28 at 7pm in France and amounted to 96.3 GW. We can see that the peak in Germany (80.7 GW) took place on the same day at 8 pm. The minimum consumption, observed on May 20 at 6 am (respectively August 12 at 7 am) in Germany (respectively France), reached 36.4 GW (respectively 30.4 GW).

Figure 2. Hourly Electricity Demand, 2018 (Source ENTSO-E)

Hydroelectricity and bioenergies are then subtracted from total demand (see Figure A.2 in the Appendix for total demand less those production sources).

Supply and CO2 emissions. We consider ten production technologies: nuclear power plants (NPP), coal-fired facilities (COAL), offshore wind power plants (Windoff); onshore wind power plants (Windon); photovoltaic power plants (PV); gas cogeneration plants (COGG); Combined Cycle Gas Turbine (CCGT), gas turbine power plants (TACG); fuel oil power plants (FUEL), and fuel oil-fired turbines (TACF). We distinguish between old power plants and new ones based on their costs[16] as Table 2 shows. This latter also provides information on the production capacity[17] of each type power plants in 2018 in France and Germany respectively.

For thermal production, we consider constant availability rates (see Table 2), whereas for intermittent sources (wind and solar) we use variable availability rates as Figure 3 shows.

[16] We assume that technologies are the same for both countries as in a short-term period fixed operating costs of existing power plants are substantially similar (RTE, 2017).

[17] Sources : RTE (2019) for France and Birger (2019), Fraunhofer-ISE (https://www.energy-charts.de/power_inst.htm) and Umwelt Bundesamt (https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/energieverbrauch-privater-haushalte) for Germany; we refer to Komusanac et al. (2019) or EEG in Zahlen 2018 – Inhaltsverzeichnis for wind information (https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEGinZahlen_2018_BF.pdf?__blob=publicationFile&v=2).

	Existing capacities		Average availability rate of thermal power plants (Percent)	
	MW			
	France	Germany	France	Germany
NPP	63 130	9516	71*	91.2*
Windoff	2	6396	See Figure 3	
Windon	15 314	52447		
PV	8 527	45230		
COGG	4 860	18747	97	
CCGT	11 448	15100	95	
TACG	703	18747	97	
CoalB	2 004	20859	92.5	
CoalH	993	23780	92.5	
Fuel	3 440	4300	97	

** 92% maximum availability rate for nuclear power.*

Table 2. Existing capacities and availability rates

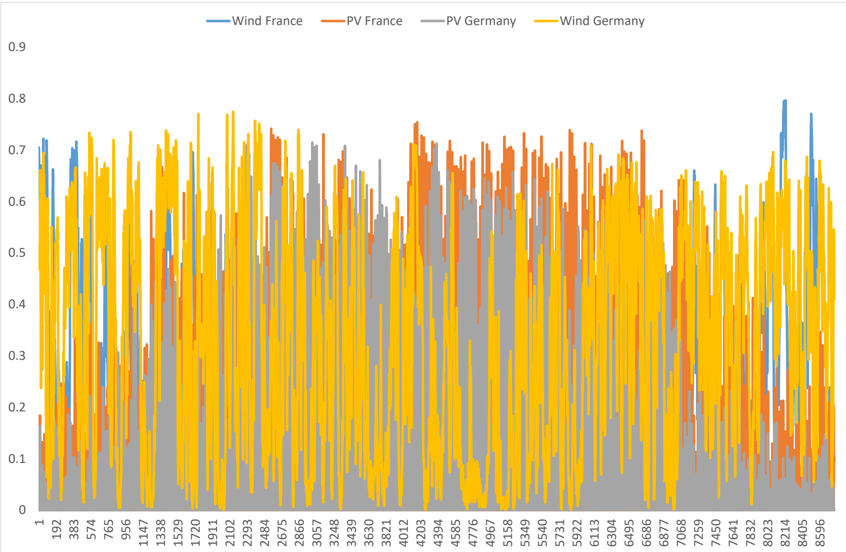


Figure 3. Availability rates for PV and wind.

We have considered 1530 MW load shedding potential[18] according to available data on interruptible contracts capacity[19] and 2 GW[20] in Germany. Load shedding costs is assumed to be 9343€/MW[21].

Table 3 portrays the efficiency (r) and CO_2 emissions (e) respectively of thermal units (except nuclear plants). By denoting by p_j^y the fuel price for technology j over the year y, the short-run marginal cost of production and pollution of technology j are $mc_j = p_j^y/r + \sigma \times e_j$ with $j \in \{COGG; CCGT; TACG; CoalB; CoalH, Fuel\}$. We make the assumption of a variable fuel cost of 11.09€/MWh.

	COGG	CCGT	TACG	CoalB	CoalH	Fuel
Efficiency rate (*r*)	0.48	0.57	0.35	0.45	0.4	0.35
Emission factor (*e*) tCO_2/MWh	0.583	0.352	0.583	0.986	0.986	0.777

Table 3. Efficiency levels and emission factors (Source: RTE, 2019)

[18] RTE (2018) reports to a maximum of 1075 MW of load shedding activated in 2018.
[19] https://www.lemondedelenergie.com/europe-blackout-electricite/2019/01/17/
[20] https://ec.europa.eu/commission/presscorner/detail/en/MEMO_18_681
[21] https://media.opera-energie.com/baisse-prix-capacite-elec/

For the reference year (2018), we assume 80.0€/t[22] for coal; 22€/MWh for gas; 60.7€/bbl for oil.[23] Table 4 reports the resulting CO_2 fuel switching prices.

€/t	COGG	CCGT	TACG	CoalB	CoalH	Fuel
COGG		-31.33	-1.00	59.53	52.75	-320.74
CCGT	-31.33		-105.02	26.42	22.12	-163.44
TACG	-1.00	-105.02		101.77	94.99	-232.99
CoalB	**59.53**	**26.42**	**101.77**		-1.00	412.50
CoalH	**52.75**	**22.12**	**94.99**	-1.00		399.44
Fuel	-320.74	-163.44	-232.99	**412.50**	**399.44**	

Application: when the CO_2 price is bigger or equal to 22.12€/t, part of CoalH production will be substituted by CCGT. A negative CO_2 fuel switching price, as for example -31.33 implies that for any CO_2 positive price, one technology will displace all the others, in the merit order as well.

Table 4. CO_2 fuel switching prices

The interconnection capacities between the two countries are: $T_{F \to G}$ = 1800 MW and $T_{G \to F}$ = 3000 MW.

3.2. Results

Algorithm. We use GAMS with MINOS to solve the optimization problems.

3.2.1 Model calibration: German and French electricity markets

To ensure model consistency, we first neglect emission constraints and exogenous electricity import export between France, Germany and the rest of European countries. France and Germany are big electricity net exporters (60 TWh for France[24]– and 51 TWh for Germany[25]). French demand is domestic consumption augmented by electricity export (except for the group Germany Belgium which are coupled in the data). Table 5 shows the simulation against real data. Notice that 18.7Mt corresponds to 20.4 Mt French emissions (RTE, 2018) less 1.7 Mt from waste. We slightly undervalue German emissions (264.5 instead of 273, that is, the real figure),[26] as we only model exports toward France.

Emissions in Mt	France	Germany
Domestic + Export to F	11.03	260.68
Export F/G	7.63	3.86
Total	18.66 (18.7)	264.54 (273)

Table 5. CO2 emissions (for Germany, export to France only).

3.2.2. The benchmark

The benchmark model only takes into account trade between Germany and France and no market for CO_2 emissions.

[22] Approximately 9.83 €/MWh.
[23] Approximately 37.82 €/MWh.
[24] See RTE (2018)
[25] See https://allemagne-energies.com/2019/01/07/le-paysage-energetique-allemand-en-2018/
[26] On German emissions : https://allemagne-energies.com/2019/01/07/le-paysage-energetique-allemand-en-2018/

Production. The minimum cost solution to satisfy demand is as follows:

TWh	NPP	COALB	COALH	WINDM	WINDT	CCGT	PV	COGG	Total
F ->F	368.70	1.34	0.33	0.00	20.72	0.59	6.09	0.00	397.78
F->D	3.05	0.04	0.05	0.00	7.41	0.09	4.50	0.00	15.13
Prod F	**371.76**	**1.37**	**0.38**	**0.00**	**28.13**	**0.68**	**10.58**	**0.00**	**412.91**
D -> D	75.97	156.12	95.37	11.82	99.34	7.18	45.89	0.04	491.73
D -> F	0.11	0.10	0.21	0.07	0.04	0.12	0.00	0.00	0.63
Prod D	**76.08**	**156.21**	**95.58**	**11.88**	**99.38**	**7.30**	**45.89**	**0.04**	**491.73**

Table 6 Production in TWh by each technology (except for hydro and biomass)

No load shedding is needed. In particular, 92.5% of French demand is satisfied by the nuclear fleet, with very low import (net of hydro and bioenergy that we don't consider). German nuclear production satisfies less than 15% of the country's considered demand. The production of coal technologies satisfies 49.2% of German consumption. The share of imports is higher than in France but remains low (less than 3%). Figures 4 - 5 display production of each technology to satisfy demands. Because of the production facilities of the two countries, French electricity consumption is satisfied by very low-emission technologies, unlike that of Germany.

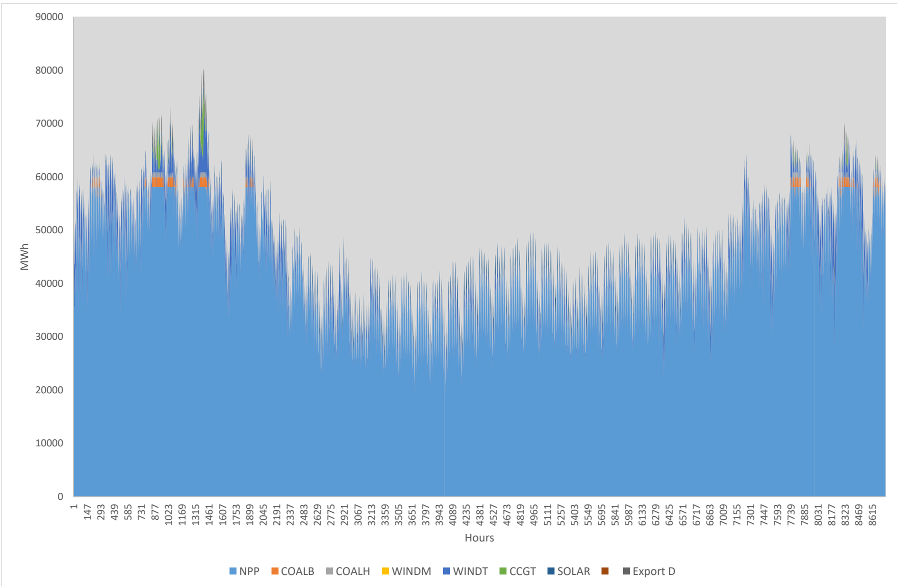


Figure 4 Technologies in France

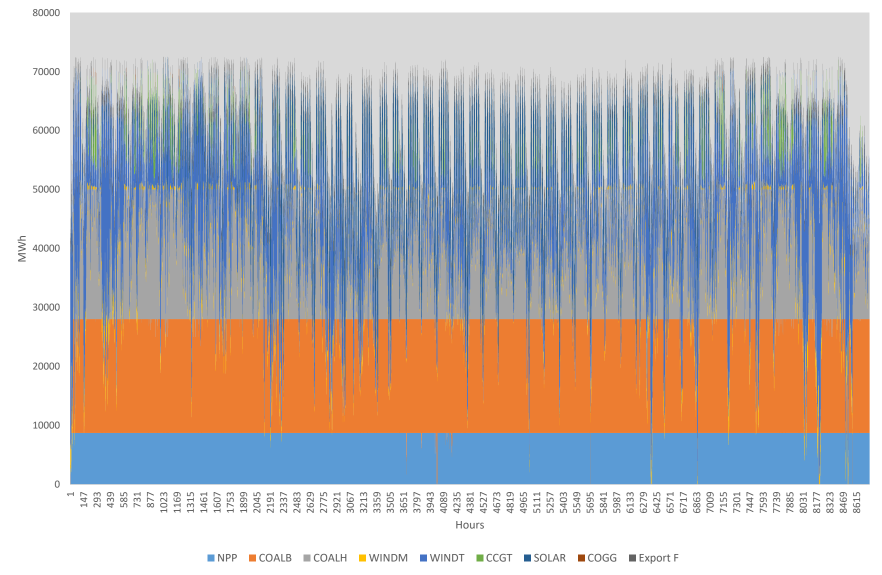


Figure 5 Technologies in Germany

Emissions. Under the assumption on no interconnection of France and Germany with other European countries, emissions are as follows:

Emissions in Mt	F	D
Domestic	1,86	250.25
Export F/D	0.11	0.22
Total	1.97	250.74

Table 7 CO_2 emissions if France and Germany are not connected with other countries

Notice that import/export does not generate important emissions.

Prices. Hourly prices (i.e. the dual value of the demand constraint) are summarized in Table 8, which gives the minimum, maximum, average and median prices for the two countries. Statistics on transport prices between the two countries (or cost of interconnection between the two countries which represents the dual value of the capacity constraint) are also presented. France exported 8259 hours toward Germany.

Price	€/MWh	min	max	moyen	médiane
Energy	France	11.1	38.6	12.89	11.1
	Allemagne	0	45.8	26.35	24.57
Transport	France → Germany	2.73	34.74	14.51	13.49
	Germany → France	2.73	16.75	13.48	14.02

Table 8 Statistics on hourly electricity and interconnection prices

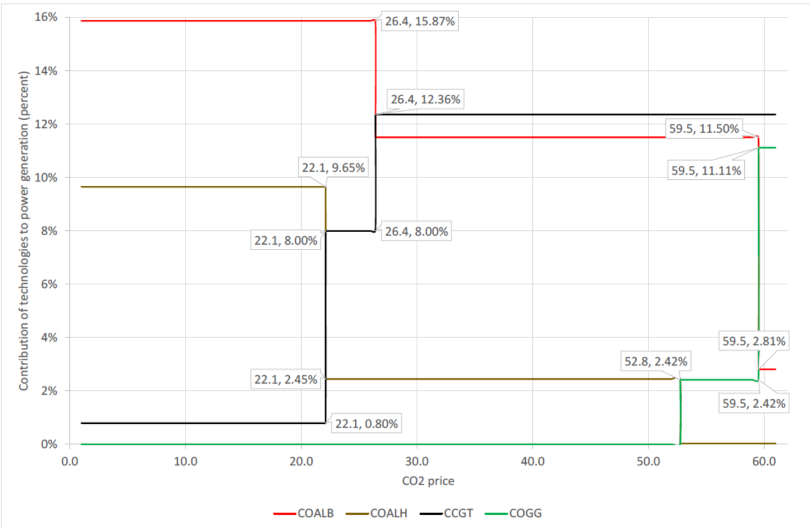
3.2.3 Introducing the CO_2 market

3.2.3.1. No price floor

Production. Regardless of the price of CO_2, the shares of the different technologies to meet both French and German demand (displayed in Figures 4—5) are as follows: 45.08% nuclear; 1.21% offshore wind; 12.84% onshore wind; 5.70% PV and 8.86% hydro plus bioenergy. The other tail concerns the distribution of the remaining technologies. Figure 6 illustrates the merit order for a CO_2 price up to 62 euros.[27] Each step correspond to a CO_2 switching price.[28] When the CO_2 price is equal to a CO_2 fuel switching price, then, as Proposition 3 in section 2 points out, several production shares lead to the same minimum costs to meet demand (multiple equilibria). The height of the "steps" of the functions shown in Figure 6 illustrates these different optimal distributions.

CO2 market. Supply shown in Figure 6 generates programs shown in Figure 7. As noted in 2.2.2, the inverse CO_2 emission demand function for the two countries as a whole is staggered and each step corresponds to a CO_2 fuel switching price. The values for the total demand for CO_2 emission permits are those in Table A.2 of Appendix A.2.

The price as well as the equilibrium quantities on the CO_2 market are deduced from this inverse demand curve and the supply of A permits. Thus, for any quantity $A > 251.71$ Mt the CO_2 price drops to zero.[29] If $A < 120.46$ Mt the emission constraint cannot be met (in the short-term). What happens if A is between 2 steps of the inverse CO_2 demand curve, i.e. $\underline{A} < A \leq \overline{A}$ with $120.46 \leq \underline{A}$ and $\overline{A} \leq 251.71$? In this case, the price will be the maximum price of the inverse demand function when the issued permits are $\overline{A}$. For example, if A is such that $207.36 < A \leq 252.71$ Mt the equilibrium price will be 22.12€/MWh.

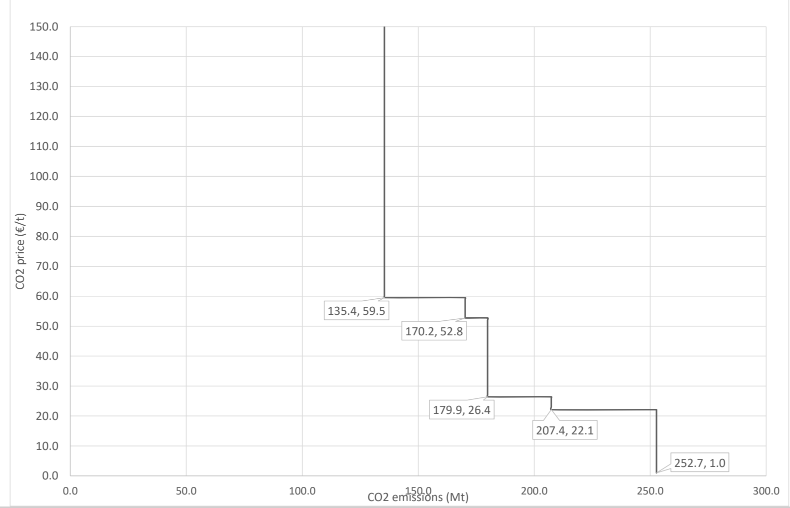


Interpretation: The step functions represent the distribution of the emitting technologies in the total production (France and Germany) when the CO_2 price is less than or equal to 62€/t. These functions are staggered, and each "step" corresponds to a CO_2 fuel switching price. When the CO_2 price is equal to a CO_2 fuel switching price, several production distributions lead to the cost minimization in order to satisfy demand.

The height of the "steps" illustrates different optimal distributions. For example, if the CO_2 price is equal to 22.12€/t, then it is indifferent to use CCGT and COALH. When CO_2 price is less than 22.12€/t, it is less expensive to produce with COALH than with CCGT. The share of COALHs in the production to satisfy the demands considered is in this case 9.65%. However, due to production and transmission constraints, the CCGTs produce (0.80% of production). When the CO_2 price is higher than 22.12€/t, it is cheaper to produce with CCGTs. When this price is between 22.12€/t and 26.42€/t (excluded) the production of CCGTs represents 8.00% of the total production and that of COALHs 2.45%. When the CO_2 price is 22.12€/t, COALH is optimal for $9.65 - \alpha$ and CCGT $0.80 + \alpha$ with $0 \leq \alpha \leq 7.2$.

Figure 6 Contribution of CO_2-emitting technologies to power generation

[27] Similar effects obtain for a higher CO_2 price.
[28] See Table 4 for CO_2 fuel switching price value.
[29] We consider only a plausible allocation for the French and German emissions.



Interpretation: The step function represents the inverse demand for global emission permits derived from the sum of the demands of the two countries. This inverse demand function has been truncated at 150€/tCO_2. If the number of permits placed on market *A* is greater than 251.71 Mt, the price of the permit will be zero. Each step corresponds to a CO_2 fuel switching price. Assumption 1 is not made here. Consequently, there can be several equilibria when the CO_2 market price is different from a CO_2 fuel switching price (see Proposition 1).

Figure 7 Inverse total demand for emission permits

Trade. Annual exports between the two countries as a function of CO_2 price are shown in Figure 8. France exports more electricity to Germany than Germany exports to France. An increase in French annual exports does not necessarily imply a decrease in German exports.

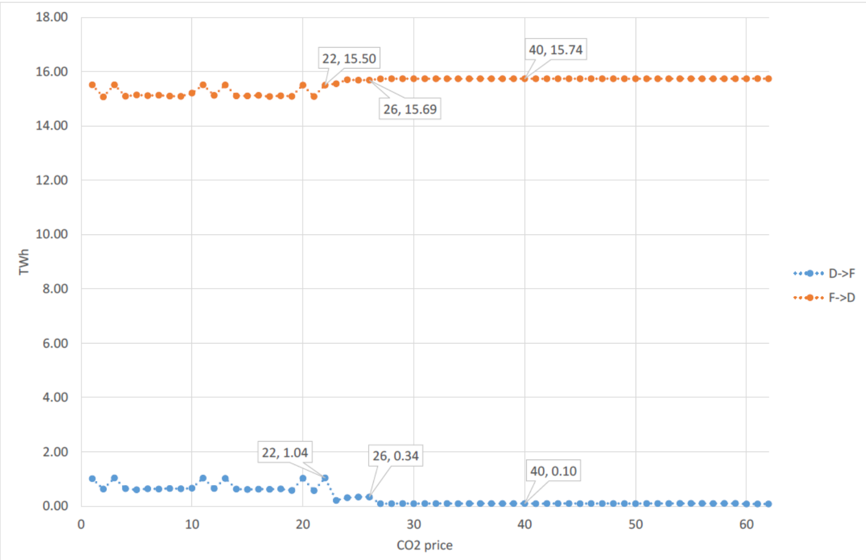


Figure 8 Annual exchanges between France and Germany as a function of the CO2 price

3.2.3.2. With a CPF

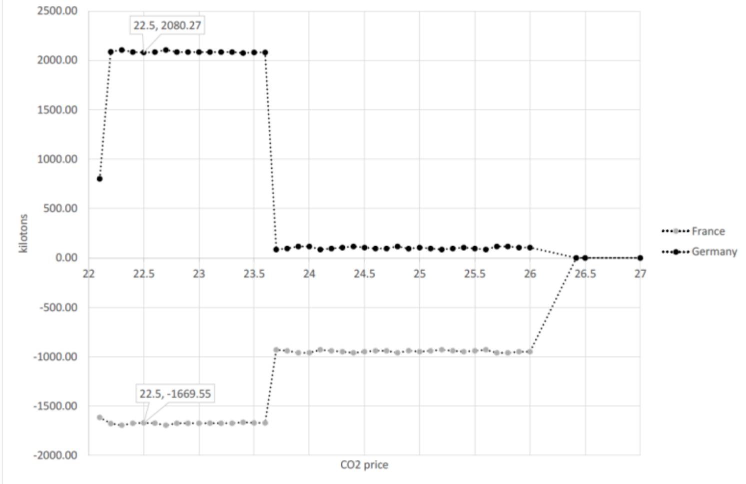
The first CO_2 price threshold being 22.12€/t, any CPF below this threshold will have no impact on production and therefore emissions. We look at the impact of four price floors (close to CO_2 fuel switch prices): 25; 30; 55 and 60€/t respectively. The study of the impact of a CPF only in France (asymmetric regulation) illustrates Theorem 1 of Section 2. With regulation in both countries, we illustrate Proposition 6 in section 2.

a. Asymmetric Regulation: impact of a CPF in France

Emission permits demand. The phenomenon highlighted in the analytical case is that a CPF not imposed on all countries that must purchase CO_2 emission permits can, for certain values of the price of CO_2, generate an increase in the total demand for emission permits. Indeed, our simulations show that when the market price of CO_2 is close to the switching price which is lower than the CPF, then it is possible that the total demand for CO_2 emission permits will increase (see Figure A.4 of Appendix 4 represents the difference between the emissions with CPF and the emissions without CPF). In our numerical application this increase is small compared to the overall emissions. This can be explained, on one hand, by the interconnection capacity constraint and, on the other hand, by the low use of polluting technologies used in France which will be replaced by more polluting technologies from Germany. Thus, if a CPF of 30€/t of CO_2 is imposed in France, for any market price below 22€/t, the CPF will contribute to reducing the CO_2 emission permits demand. We can see that a price of 23€/t, 24€/t or 27€/t the demand for emission permits will be higher with a CPF than without. Above 30€/t there will be no impact (the CPF is no longer binding).

Production. The changes in CO_2 emission permits demand following the introduction of a CPF in France are due to changes in the production technologies used. By way of illustration, we study what happens on whether a "regulator" wants coal-fired power plants to be placed after CCGTs in order of merit. Given the fuel switching prices, it is useful to study a price floor at 26.43€/t (above that value, there is no impact). We zoom in the interval [22.1; 27] on the CO_2 market.

In Figure 9, the difference between emission permit demand in France (resp. Germany) with a CPF of 26.43€/t imposed in France and those without a CPF is shown in light grey (resp. black). The demand for French CO_2 emission permits decreases and those for Germany increases (*waterbed effect*). We can see that when the market price of CO_2 is between 22.2€/t and 23.6€/t the increase in demand for CO_2 emission permits in Germany is greater than the decrease observed in France. Consequently, over this range, the CPF of 26.43€/t in France contributes to increase the overall demand for emission permits.



Interpretation. If the market price is 22.5€/t, then a CPF of 26.43€/t in France will increase the demand for emission permits in Germany by 2.08 Mt and decrease the demand in France by 1.67 Mt. Consequently, the overall demand for CO_2 emission permits when the market price is 22.5€/t increases by 0.41 Mt if a CPF of 26.43€/t is imposed on France. As a result, if supply remains the same and is constraining, the CO_2 price must adjust i.e. increase. The equilibrium emissions will be the same and the waterbed effect will be observed.

Figure 9 Emission permits demand with a CPF in France: differences with respect to the case without CPF

To understand the increase in the global demand for emissions permits when a CPF of 26.43€/t is imposed in France and when the market price of CO_2 is between 22.2€/t and 23.6€/t, we look at how emissions vary according to the CO_2 market price with and without this CPF (Table 9). Supplies without a CPF are written in grey and those with a CPF in black.

Given our cost and emission factor assumptions, 22.12€/t is the price of CO_2 at which the CCGT units substitute the COALH units in order of merit (see Table 4). Consequently, when there is no CPF, the production of COALHs (resp. CCGTs) is lower (resp. higher) when the market price of CO_2 is higher than 22.12€/t (see the numbers highlighted in green in Table 9). The total production of COALB units is the same when the market price of CO_2 is below 26.42€/t, but it can vary in each country (not a single equilibrium). Thus, in Table 9, we can also see variations in the production of COALB units in the two countries when the market price of CO_2 goes from 22.1€/t to 22.2€/t: decrease of 2314 MW in France (increase of 2314 MW in Germany). With a CPF of 26.43€/t effective in France only, the CO_2 fuel switching prices are no longer the same between countries (see Appendix A.4.).

- Over the range of CO_2 prices studied (22.1; 23.6) France does not produce with COALH power plants and reduces the production of these COALB units compared to the case without a CPF. Its CCGT capacities are not sufficient to avoid the production of coal-fired power plants (production of 4447 MW of French COALB units).
- Due to the asymmetric regulation, German coal-fired power plants are more competitive than French ones. Moreover, since the market price of CO_2 is below 26.42€/t, German COALB units are cheaper than French CCGT units. As a result, the introduction of the CPF of 26.43€/t in France contributes to the increase in production of German coal-fired power plants. The increase of this production is higher than the decrease of the production of French power plants when the CO_2 price is below 26.42€/t. Thus, if we

consider that the market price of CO2 is 22.2 €/t, the decrease (resp. increase) of the annual production of French (resp. German) coal-fired power plants is 1.37 TW (resp. 2.02 TW). Given our assumptions on CO_2 emission factors, the introduction of the CPF of 26.43€/t in France contributes to increase the emissions of coal-fired power plants from when the market price of CO_2 is 22.2€/t to 0.64Mt. French (resp. German) CCGT production decreases (resp. increases) by 0.95 TW (resp. 0.27) for a total decrease of 0.65 TW. The introduction of the CPF of 26.43€/t in France contributes to reduce emissions of CCGT by 0.23 Mt. The increase in emissions from coal-fired power plants (0.64 Mt) and the decrease in emissions from CCGTs (0.23 Mt) leads to an increase in CO_2 emissions of 0.41 Mt. This effect resembles the "internal carbon leakage" analyzed by Perino et al. (2019).

FRANCE (MW)						
CO2 Price	**22.1**	**22.2**	**…**	**23.4**	**23.5-23.6**	**23.7**
COALB	1376471	1374157		1374157	1374157	1374157
	4447	4447		4447	4447	41330
COALH	395298	919		919	1837	919
CCGT	629356	1914597		1880026	1894654	1880026
	992424	992424		992424	992424	2972910
GERMANY (MW)						
CO2 price	**22.1**	**22.2**		**23.4**	**23.5 - 23.6**	**23.7**
COALB	156227456	156229770		156229770	156229770	156229770
	156229943	156229943		156229943	156229943	156229943
COALH	95452219	24311421		24311421	24310502	24311421
	95933562	26329709		26329709	26329709	24312339
CCGT	7275015	77524952		77559523	77544896	77559523
	8195440	77799293		77799293	77799293	77799293
COGG	44364	44364		44364	44364	44364
	44364	44364		44364	44364	44364

Explanation. In grey (resp. black) the productions when there is not (resp. when there is) a CPF of 26.43€/t imposed in France. Changes in production compared to previous prices are highlighted.

Table 9 Production by thermal units (MW) without and with a price floor fixed at 26.43€/t and imposed in France.

The possible increase in demand for CO_2 emission permits following the introduction of a CPF in only one of the two countries is only possible if the countries are interconnected. This CPF therefore has an impact on trade between the countries and we have found that when the CPF is effective, German exports are higher than in the case without the CPF.

b. <u>Asymmetric Regulation: impact of a CPF in Germany</u>

What if only Germany introduces a price floor?

Emissions. Whatever the market price of CO_2, a CPF between €25/t and €60/t will not generate an increase in the overall demand for emission permits (see Figure A.5 in Appendix 5.). Clearly, the impact is greater in Germany than in France. CPF at 30€/t and 55€/t have the same impact in terms of CO_2 emissions.

We now study what happens if the German regulator sets a CO_2 price such that coal-fired power are ranked after the CCGT in the merit order. Knowing the CO_2 fuel switching prices, he can decide on a CPF equal to 26.43€/t. We zoom in on the price range [22.1; 27] in the CO_2 market.

In Figure 10, the difference between emission permit demand in France (resp. Germany) with a CPF of 26.43€/t imposed in Germany and emissions without a CPF is shown in light grey (resp. black). The demand for CO_2 emission permits in Germany decreases strongly (around 26.77 Mt) while the French demand for emission permits increases slightly (around 0.14 Mt). This increase limited by the production capacities of French coal-fired power plants and the interconnection capacity. It should be noted that when the same CPF was imposed in France, the increase in demand for German emissions permits did not exceed 2.2 Mt and the decrease in French emissions was less than 1.7 Mt. In this configuration, the CPF has a strong local effect in Germany.

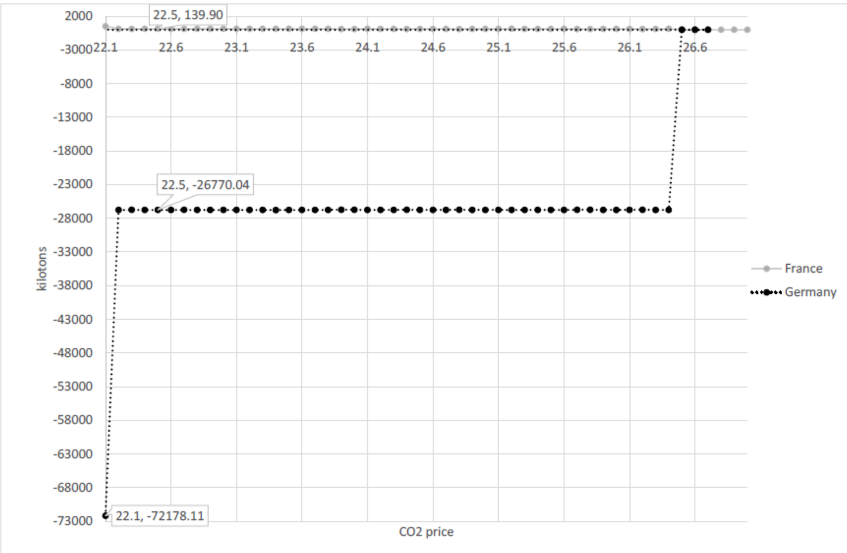


Figure 10 Emission permit demand with a CPF of 26.43 €/t in Germany: differences with respect to the case without CPF

Following the introduction of a €26.43/t CPF in Germany, German coal-fired power plants are less competitive than French ones and less competitive than CCGTs. Table 10 shows that when the CO_2 market price is between 22.1 €/t and 27 €/t, a price floor of 26.42 €/t in Germany contributes to increase (resp. decrease) the production of French (resp. German) coal-fired power plants. As the production capacity of coal-fired power plants is not sufficient to replace the production of German coal-fired power plants, Germany and France are increasing their CCGT production. As a result, French CO_2 emissions are increasing. Thus, if we consider that the market price of

CO_2 is 22.2€/t, the increase (resp. decrease) of the production of French (resp. German) coal-fired power plants is about 25 GWh (resp. 42.028 GWh) and the increase of the production of French CCGTs (resp. German) by about 309 GWh (resp. 41.695 GWh), French emissions increase by about 133 CO_2 kilotons, whereas German emissions decrease by 26.764 kilotons of CO_2 (41 440-14 676). Consequently, when the CO_2 market price is 22.2€/t and a price floor of 26.43€/t CO_2 global emissions decrease by 26.63 CO_2Mt.

FRANCE (MW)						
CO2 Price	**22.1**	**22.2**	**…**	**23.4**	**23.5-23.6**	**23.7**
COALB	1376,471	1374,157		1374,157	1374,157	1374,157
	1384,889	1384,889		1384,889	1384,889	1384,889
COALH	395,298	919		919	1,837	919
	514,726	15,242		15,242	15,242	8,811
CCGT	629,356	1914,597		1880,026	1894,654	1880,026
	1723,916	2223,399		2223,399	2223,399	2223,399
GERMANY (MW)						
CO2 price	**22.1**	**22.2**		**23.4**	**23.5 - 23.6**	**23.7**
COALB	156227,456	156229,770		156229,770	156229,770	156229,770
	114209,239	114209,239		114209,239	114209,239	114215,670
COALH	95452,219	24311,421		24311,421	24310,502	24311,421
	24303,528	24303,528		24303,528	24303,528	24303,528
CCGT	7275,015	77524,952		77559,523	77544,896	77559,523
	119219,518	119219,518		119219,518	119219,518	119219,518
COGG	44,364	44,364		44,364	44,364	44,364
	44,364	44,364		44,364	44,364	44,364

Table 10 Production technologies (MW) without and with a German CPF of 26.43€/t

The implementation of a binding CPF in Germany contributes to increasing French exports and decreasing German exports.

c. <u>CPF in both countries</u>

It is assumed here that both countries want to reduce their CO_2 emissions. For this purpose, a CPF of 26.43€/t is set up in order to place coal-fired power plants after CCGT in the order of merit. Compared to the situation without a CPF, the emissions of both countries decrease when this CPF is effective. Due to the (more coal-fired generation in Germany) the impact of the CPF is much higher in Germany than in France (see Figure 11) and Table 11. The implementation of the CPF contributes to reducing German exports and increasing French exports.

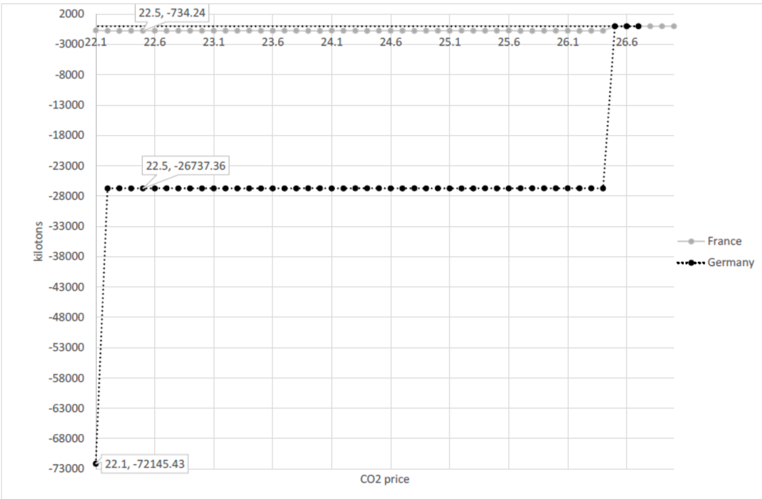


Figure 11 Emission permit demand with a CPF of 26.43€/t in both countries: differences with respect to the case without CPF

FRANCE (MW)						
CO2 Price	**22.1**	**22.2**	**…**	**23.4**	**23.5-23.6**	**23.7**
COALB	1376,471	1374,157		1374,157	1374,157	1374,157
	43,839	43,839		43,839	43,839	43,839
COALH	395,298	919		919	1,837	919
	703	703		703	703	703
CCGT	629,356	1914,597		1880,026	1894,654	1880,026
	3537,227	3537,227		3537,227	3537,227	3537,227
GERMANY (MW)						
CO2 price	**22.1**	**22.2**		**23.4**	**23.5 - 23.6**	**23.7**
COALB	156227,456	156229,770		156229,770	156229,770	156229,770
	114229,487	114229,487		114229,487	114229,487	114229,487
COALH	95452,219	24311,421		24311,421	24310,502	24311,421
	24311,636	24311,636		24311,636	24311,636	24311,636
CCGT	7275,015	77524,952		77559,523	77544,896	77559,523
	119232,923	119232,923		119232,923	119232,923	119232,923
COGG	44,364	44,364		44,364	44,364	44,364
	44,364	44,364		44,364	44,364	44,364

Interpretation. In grey (black rep.) the productions when there is not (resp. when there is) a CPF of 26.43€/t imposed in France and Germany.

Table 11 Production technologies (MW) without and with a CPF of 26.43€/t imposed in Germany and in France

4. Conclusion

Introducing price floors on specific sector or countries is not an easy task, as our model illustrates. In particular, the electricity sector, due to numerous technical and production constraints, might be particularly sensitive to the impact that CPF have on the relative competitiveness of different technologies. As we have shown, this might translate in a limited effect of CPF or even in undesirable effects, as a decrease of emission permits demand, which is a likely waterbed effect.

Our model has clearly some limitations, in that it assumes no frictions in the interconnected markets, fixed fuel prices, and no additional allocations measures as the MSR or intertemporal flexibility in the form of banking/borrowing. Also, we do not adjust the overall permits allocation, which remains fixed. Nevertheless, we believe that our results contribute to the debate on the EU ETS reform that is likely to be prompted by the new Green Deal climate objective.

References

Brnic, A. H., Thévoz L. F., 2018. EDF hopes for European CO_2 price floor within months. Montel, July 31.

Burtraw, D., Keyes A. Zetterberg L., 2018. Companion Policies under Capped Systems and Implications for Efficiency – The North American Experience and Lessons in the EU Context. RFF Working Paper.

Chaton, C., Creti A., Peluchon B., 2015. Banking and Back-Loading Emission Permits. Energy Policy, 82, 332–41.

Demertzis M., Tagliapietra S., 2021. Carbon price floors: an addition to the European Green Deal arsenal. *Bruegel Blog*, 4 March

Demirdag, J., 2018. Eleven German state ministers urge CO_2 price floor. Montel, July 16.

Edenhofer, O., Flachsland C., Wolff C., Schmid L. K., Leipprand A., Koch N., Kornek U., Pahle M., 2017. Decarbonization and EU ETS Reform: Introducing a price floor to drive low-carbon investments. Policy Paper.

Flachsland C., Pahle M., Burtraw D., Edenhofer O., Elkerbout M., Fische C., Tietjen O., Zetterberg L., 2020. How to avoid history repeating itself: the case for an EU Emissions Trading System (EU ETS) price floor revisited, Climate Policy, 20:1, 133-142, DOI: 10.1080/14693062.2019.1682494

Flachsland, C., Pahle M., Burtraw D., Edenhofer O., Elkerbout M., Fischer C., Tietjen O., Zetterberg L., 2018. Five myths about an EU ETS carbon price floor. CEPS Policy Insights, 17.

Grubb, M., Newbery D., 2018. UK electricity market reform and the energy transition: emerging lessons. Energy Journal, 39 (6) pp. 2-25.

Hintermayer, M., 2020. A carbon price floor in the reformed EU ETS: Design matters! Energy Policy 147: 111905.

Hirst, D., 2018. Carbon Price Floor (CPF) and the Price Support Mechanism. House of Commons Library Briefing Paper No. 05927. January 8.

ICAP (International Carbon Action Partnership), 2017. Netherlands Proposes EUR 18 Carbon Price Floor.

Komusanac, I., Fraile D., Brindley G., 2019. Wind energy in Europe in 2018 - Trends and statistics. WindEurope Report.

Makkonen, S., Närhi J., Patronen J., Känkänen J., Suksi T., 2019. Regional carbon price floor in EU ETS–Case studies in the Nordic and Baltic energy markets.

Newbery, D. M., Reiner D. M., Ritz R. A., 2019. The political economy of a carbon price floor for power generation. The Energy Journal, 40(1).

Pahle, M., Burtraw D., Flachsland C., Kelsey N., Biber E., Meckling J., Edenhofer O., Zysman J., 2018. Sequencing to ratchet up climate policy stringency. Nature Climate Change 8: 861–67.

Perino, G., 2019. Reply: EU ETS and the waterbed effect. Nature Climate Change, 9(10), 736-736.

Perino, G., 2018. New EU ETS Phase 4 rules temporarily puncture waterbed. Nature Climate Change 8: 262.

Perino, G., Ritz R. A., Van Benthem A., 2019. Understanding overlapping policies: Internal carbon leakage and the punctured waterbed. Cambridge Working Papers in Economics 1920, Faculty of Economics, University of Cambridge.

Perino, G., Pahle M., Pause F., Quemin S., Scheuing H., Willner M., 2021. EU ETS stability mechanism needs new design. Policy Brief, Climate Economics Chair

Roberts, M. J., Spence M., 1976. Effluent Charges and Licenses under Uncertainty. Journal of Public Economics 5, 193-208.

Rosendahl, K. E., 2019. EU ETS and the waterbed effect. Nature Climate Change, 9(10), 734-735.

RTE, 2018. Bilan Electrique 2018.

RTE, 2019. Bilan prévisionnel de l'équilibre offre-demande d'électricité en France.

Stam, C., 2018. Ministers highlight European divide over carbon price floor. Euractiv, April18.

Szabo, M., 2016. We can't wait any longer': France floats EU ETS price support proposal. Carbon Pulse, March 13.

Wood, P. J., Jotzo F., 2011. Price floors for emissions trading. Energy Policy, 39(3), 1746-1753.

Appendices

A.1. An example to illustrate theorem 1

Consider two countries ($c \in \{1,2\}$). Each country has 3 technologies $n \in \{l, m, j\}$ such as: $0 < e_j < e_l < e_m$; $\frac{p_l}{r_l} < \frac{p_m}{r_m}$ $\underline{and}$ $\frac{p_l}{r_l} < \frac{p_j}{r_j}$, then the merit order, depending on the value of σ, is the following: l, m, j if $< \sigma_{m,j} = \sigma_1$; l, j, m if $\sigma_{m,j} < \sigma < \sigma_{l,j} = \sigma_2$ and j, l, m if $\sigma_{l,j} < \sigma$. Assume that $D_2 + T_{2\to1} < K_{2,l}$ and $K_{1,l} < D_1 < K_{1,l} + T_{2\to1}$. Numerical application (NA): $D_2 = 10;\ T_{2\to1} = 8;\ K_{2,l} = 20;\ D_1 = 15\ and\ K_{1,l} = 10.$

Under these assumptions *if* $\sigma < \sigma_{l,j}$ then the demands are satisfied by the production of technology *l*. The production capacity of technology *l* is saturated in country *1*. This country imports the production of technology *l* located in country *2* (in quantity $x_{l,2\to1} = D_1 - K_{1,l}$). Consequently, the demand for CO_2 emission permits of 1 is $e_l K_{1,l}$ and that of 2 equals to $e_l(D_2 + D_1 - K_{1,l})$. The total demand for CO_2 emission permits is equal to $e_l(D_2 + D_1)$. NA: $x_{l,1\to1} = 10;\ x_{l,2\to1} = 5;\ x_{l,2\to2} = 10.$ *Let* $e_l = 0.5$ *then* $\forall\sigma < \sigma_{l,j},\ z_1(\sigma) = 5\ and\ z_2(\sigma) = 7.5$. *Therefore, the total emissions are equal to 12.5.*

A CPF, $\underline{\sigma}$ is imposed on country *2* so that it uses technology *j* before technology *l*. Hence, $\underline{\sigma} > \sigma_{l,j}$. Assume that for all $\sigma \le \underline{\sigma}$ we have $\frac{p_m}{r_m} + \sigma e_m < \frac{p_j}{r_j} + \underline{\sigma} e_j$ (i.e. it is less expensive to use the technology *m* of *1* than the technology *j* of *2* then the demand for CO_2 emission permits may increase. Indeed, if $K_{1,m} > D_1 - K_{1,l}$ and if $\sigma < \underline{\sigma}$ then the demand for CO_2 emission permits of *1 is* $E_1 = e_l K_{1,l} + e_m\left(D_1 - K_{1,l} + \min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}; D_2\right)\right)$.

If $D_2 < \min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}\right)$ the demand for CO_2 emission permits of 2 will be zero and $\min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}; D_2\right) = D_2$. The total demand for CO_2 emission permits will be equal to $e_l K_{1,l} + e_m\left(D_1 - K_{1,l} + D_2\right)$ i.e. an increase in demand for CO_2 emission permits compared to the case without a CPF equals to $(e_m - e_l)\left(D_1 + D_2 - K_{1,l}\right)$.

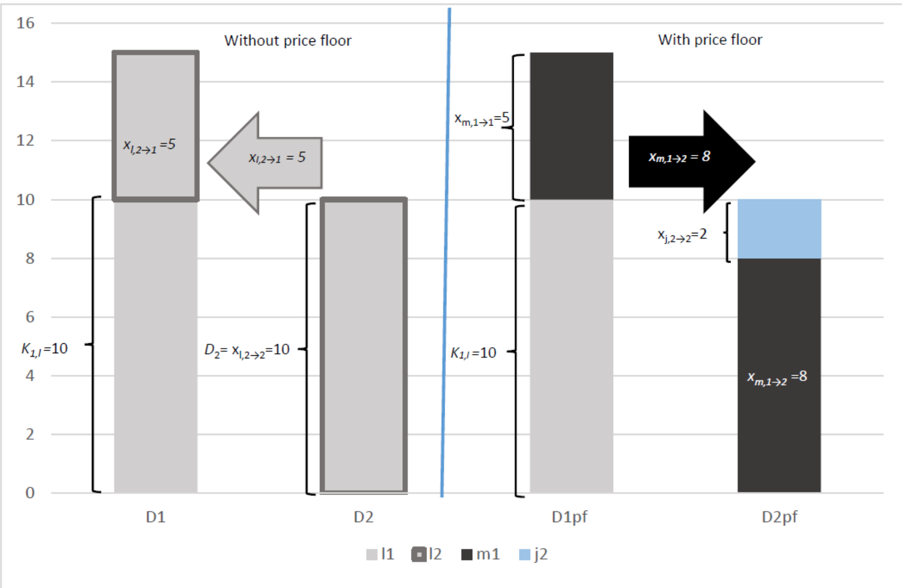
If $D_2 > \min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}\right)$ then $x_{j,2\to2} = D_2 - x_{m,1\to2}$. The demand for CO_2 emission permits of 1 will be equal to $E_1 = e_l K_{1,l} + e_m\left(D_1 - K_{1,l} + \min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}\right)\right)$ and the demand for CO_2 emission permits of *2* will be equal to $E_2 = e_j\left(D_2 - \min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}\right)\right)$. In this case, the overall demand for CO_2 emission permits will increase compared to the situation without a CPF if $\min\left(K_{1,m} - D_1 + K_{1,l}; T_{1\to2}\right) > \frac{(e_l - e_j)D_2 - (e_m - e_l)(D_1 - K_{1,l})}{e_m - e_j}$.

Numerical example: Let $K_{1,m} = 20$; $e_m = 0.8\ and\ e_j = 0.2$. *We have* $D_2 = 10 > \min(20 - 15 + 10; 8) = 8$; $x_{l,1\to1} = 10;\ x_{m,1\to1} = 5;\ x_{m,1\to2} = 8\ et\ x_{j,2\to2} = 10 - 8 = 2$. *As a result* $\forall\sigma < \underline{\sigma},\ z_1(\sigma) = 0.5 \times 10 + 0.8(5 + 8) = 15.4\ and\ z_2(\sigma) = 0.2 \times 2 = 0.4$. *Therefore, the total demand for* CO_2 *emission permits is equal to 15.8. In this numerical application, the introduction of a CPF in country 2 has contributed to decrease the demand for* CO_2 *emission permits of this country but to increase the demand of country 1 and finally to increase the total demand for* CO_2 *emission permits. As a result, it is possible that the introduction of an asymmetric CPF contributes to increase the total* CO_2 *emissions. But this result is based on the following conditions:*

- *if the supply of* CO_2 *emission permits is the same with or without a CPF, this supply should not be binding without a CPF (i.e. the price of the permits is zero without a CPF) so that the increase in* CO_2 *emissions is possible;*
- *if the permit supply is binding without CPF then this supply must increase with CPF!*

Consequently, if the supply of CO_2 emission permits is not modified with this asymmetrical regulation, and if it is binding with the CPF, then an increase in the demand for CO_2 emission permits following the introduction of this asymmetrical CPF generates an increase in the price on the CO_2 market.[30] And, if the price of CO_2 permits is positive without a CPF (supply of permits less than or equal to demand) then this increase in demand for CO_2 emission permits generates a "waterbed effect".

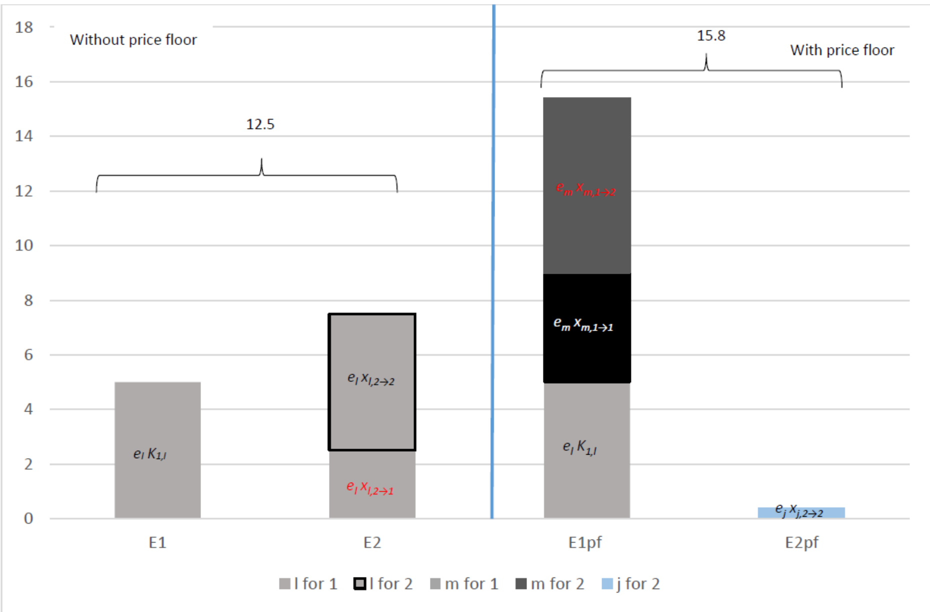
Figure A.1.1 and Figure A.1.2 illustrate the possible increase in CO_2 emissions permit demand (for a given price of CO_2) following the establishment of an asymmetric CPF. The data used are that of the above numerical application. Figure 1 shows the stacking in the demand of production technologies (merit order) without CPF and with CPF. Figure A.1.2 shows the resulting CO_2 emissions.



Interpretation: Without CPF, the demands (D1 and D2) are satisfy by the production of the technology *l*. Country 1 imports (shaded arrow) from the production of the technology *l* of 2 noted l2 (in quantity $x_{l,2\to1}=5$). D1pf and D2pf represent the stacking of technologies to satisfy demands when a CPF is imposed in country 2 and not in 1 and such that this CPF implies that it is cheaper to use *m* of 1 (m1) than *j* of 2 (j2). In the example, D2pf is not only satisfied by m1 (because either the capacities of m1 or those of the interconnection are saturated) i.e. $D_2 > \min(K_{1,m} - D_1 + K_{1,l}, T_{1\to2})$.

Figure A.1.12 Demand satisfaction without and with asymmetric price floor

[30] This is illustrated in Figure 1 of 2.3.2.



Interpretation: Without a CPF the emissions in 2 are mainly due to exports (grey boxed rectangle). With price floor the technology *j* of 2 (j2) is no longer used. In its place the technology *m* of 1 with a higher emission factor and then the technology *j* of 2 with a lower emission factor are used. In this example, the CPF on the electricity market of country 2 strongly reduces its emissions but increases the emissions of country 1 much more. Finally, the impact of the CPF on country 2 generates an increase in total emissions (from 12.5 units to 15.8 units) for a "fixed" price of CO_2 or variable CO_2 permit supply.

Figure A.1.13 Emissions corresponding to the productions shown in Figure 1 under the assumptions that ej = 0.2; el = 0.5 and em = 0.8.

A.2. Electricity demands considered

Figure A.2 represents the annual demands we considered, i.e. the hourly demands of France and Germany minus the production of hydro and bioenergy technologies.

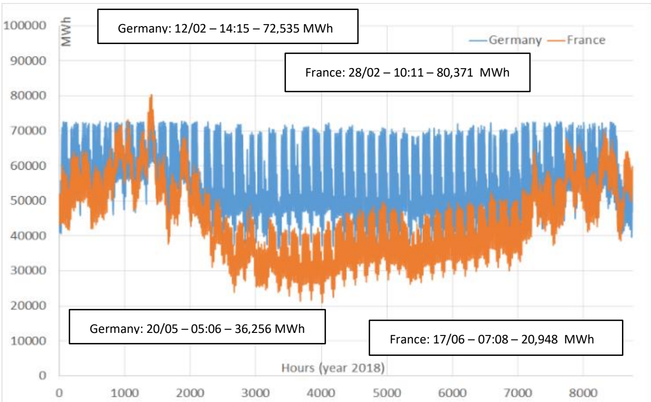


Figure A.2 Electricity demands minus the production of hydro and bioenergy technologies

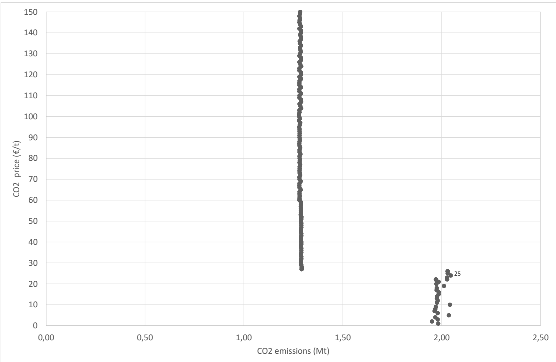
A.3. Emissions and demand of CO_2 emissions permits

Table A.3.1 gives global emissions for different CO_2 prices. The CO_2 fuel switching prices and the associated technology changes are also detailed.

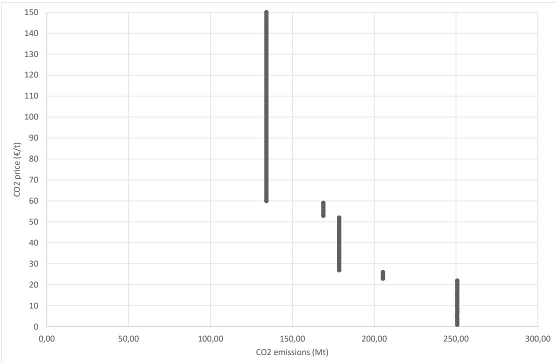
CO_2 price (€/t)	Emission (Mt)	Technology changes
< 22.12	252.71	
= 22.12	from 207.36 to 252.71	Part of the CoalH is replaced by CCGTs
22.12 < σ < 26.42	207.36	
=26.42	from 179.89 to 207.36	Part of the CoalB is replaced by CCGTs
26.42 < σ < 52.75	179.89	
= 52.75	from 170.22 to 179.89	Part of the CoalH is replaced by COGGs
52.75 < σ < 59.53	170.22	
= 59.53	from 135.41 to 170.22	Part of the CoalB is replaced by COGGs
59.53< σ < 392.05	135.41	When σ = 101.77, a very small part of the Coal B production of is replaced by Gas Turbines (TACG), but there is no change in the amount of CO_2 emissions in our case study.
= 392.05	from 135.35 to 135.41	Part of the Coal H is replaced by Fuel
392.05< σ < 405.12	135.35	
= 405.12	from 132.76 to 135.35	Part of the Coal B is replaced by Fuel
405.12 < σ < 9453.50	132.76	
=9453.50	132.76	Part of the Coal B is replaced by load shedding
9453.5 < σ < 11887.37	132.76	
=11887.37	from 126.6055 to 132.76	Part of the Fuel is replaced by load shedding
11887.37<σ <15917.91	126.6055	
=15917.91	from 126.6051 to 132.76	Part of the TACG is replaced by load shedding
15917.91< σ < 15947.11	126.6051	
=15947.11	121.57 to 126.6051	Part of the COGG is replaced by load shedding
15947.11< σ <26432.96	121.57	
= 26432.96	from 120.46 to 121.57	Part of the CCGT is replaced by load shedding
26432.96 > σ	120.46	120.46 Mt is the minimum amount of CO_2 that can be achieved taking into account the demands, the production and interconnection capacities and load shedding

Table A.3.1 Total emissions depending on the CO_2 price

Figures A.3.a – A.3.b represent the inverse CO_2 permit demands for the two countries corresponding to an equilibrium.



a. French inverse demand of CO_2 permits



b. German inverse demand of CO_2 permits

Interpretation: For a CO_2 price, the points in these figures represent the CO_2 emissions for an equilibrium. We can see that for France these points are not aligned. It is the same for Germany, but the variations with respect to the quantity emitted from this country are too small to visualize them. These two figures are linked - due to the existence of the interconnection. Thus, when a point on Figure a is positioned on the right with respect to the point just below it, the equivalent point on Figure b will be positioned to the left with respect to the point just below it. Variations are associated with variations in trade between these 2 countries. Note that this does not necessarily mean that the increase in French exports generates a decrease in German exports. The shifts are the same in absolute value, so that between two CO_2 fuel switching prices the global demand function of the permits is a line (not shown here).

Figure A.3 Inverse demands of CO_2 permits

A.4. Impact of a CPF in France

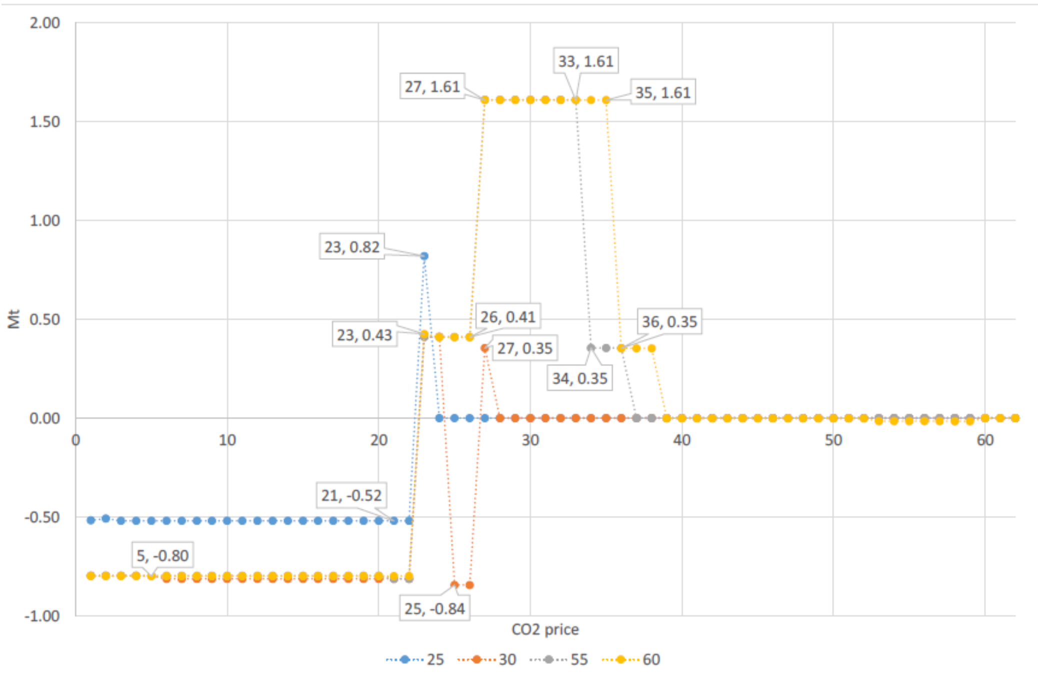
Table A.4 gives the "country CO_2 fuel switch price" (defined in 2.3.2.) when the CPF is €26.43 per ton. When the boxes are empty it means that $\sigma_{n,n'}(\underline{\sigma}) > \underline{\sigma}$, in this case, the CO_2 fuel switch price defined in Table 4 must be considered.

Germany \ France	COGG	CCGT	TACG	CoalB	CoalH	Fuel
COGG	26.43	3.54		3.55	8.24	
CCGT		26.43				
TACG	-2.77	-25.66	26.43	-25.65	-20.96	
CoalB		26.43		26.43		
CoalH		**23.66**		**23.66**	26.43	
Fuel	-60.25	-77.42	-38.34	-77.42	-73.90	26.43

Interpretation: When a CPF of 26.43 €/t is imposed in France and if the CO_2 price is higher or equal to 23.66 €/t then the short-term cost of French CCGTs is lower than that of German COALHs.

Table A.4 Country CO2 fuel switching prices when a CO2 price floor of 26.43€/t is imposed in France

Figure A.4 gives, for certain values of CO_2 price on the market[31], the impact on emissions of a CPF in France when it is equal to 25, 30, 55 and 60€/ton.



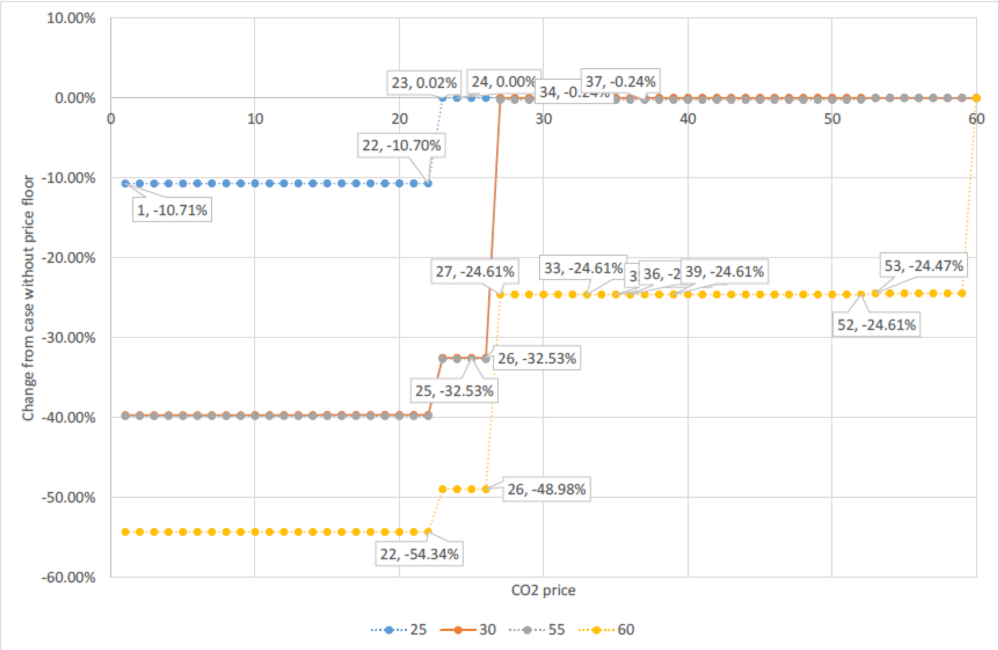
Interpretation: If a CPF of 25€/t is imposed in France (blue dots) and if the price on CO_2 market is 23 €/t then the global annual CO_2 emission demand with a CPF will be higher (+ 0.82 Mt) than those without CPF. Note that French CO_2 emission demand without a CPF when the CO_2 price is 23€/t are 2.03 Mt.

Figure A.4 Impact of price floor (25€/t, 30€/t, 55€/t and 60€/t) in France on CO_2 emissions demands as functions of market CO_2 price

[31] We have simulated these demands only for integer values of the CO_2 price. As a result, only points should be represented in Figure A.4, but for ease of reading we have linked these points.

A.5. Impact of a CPF in German

Figure A.5 gives, for certain values of CO_2 price on the market,[32] the impact on emissions of a CPF in German when it is equal to 25, 30, 55 and 60 €/t.



Interpretation: If the CPF considered and imposed on Germany has an effect, it generates a decrease in total demand of CO_2 emission permits.

Figure A.14 Impact of CPF (25€/t, 30€/t, 55€/t and 60€/t) in German on CO_2 emissions demands as functions of market CO_2 price.

[32] Same remark as in the previous footnote.

WORKING PAPER

PREVIOUS ISSUES

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