Carbon Contract for Differences for the development of low-carbon hydrogen in Europe*

Corinne Chaton[1,2] and Coline Metta-Versmessen[1,3]

[1]EDF R&D, Palaiseau, France.
[2]Finance for Energy Market Research Centre (FIME), Paris, France.
[3]University of Paris Dauphine, Climate Economics Chair, Paris, France.

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Abstract

While developing a low-carbon hydrogen economy in the European Union is currently an energy transition keystone, electrolysis based production is not yet competitive compared to steam reforming. This study aims to characterize a new political tool, the Carbon Contract for Difference (CCfD), in the specific case of scaling up electrolysis based hydrogen production. Our analysis suggests that an economically efficient CCfD can be defined for each area with homogeneous electricity mix. This CCfD should be designed depending on the gas prices and the current State aids being used in the EU-ETS system. This paper offers a methodology for policy makers to design CCfD according to their region and the sector application.

Key words: CCfD, low-carbon hydrogen, emission reduction, EU-ETS.
JEL Codes: D47, Q48, Q52.

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1 Introduction

Low-carbon hydrogen is now a crucial tool for the energy transition. Produced without emitting greenhouse gases, this dihydrogen (H2) commonly called decarbonized hydrogen, is a gas with many virtues. In the European Union, most of Member States see it as beneficial for the depollution of sectors with high marginal decarbonation costs and for the flexibility of energy networks [FCH2JU, 2020].

Thus, in 2018, Europe has a hydrogen production capacity of 9.9 million tons per year [Hydrogen Europe, 2020b]. Hydrogen demand comes mainly from refineries and the chemical industry, accounting for 93% of consumption. The rest of the demand is divided between metallurgy, food processing, energy production and transportation. However, the production of hydrogen is currently very polluting since it is based on the vaporization of fossil energy (SMR, for "Steam Methan Reforming") for 95% of its production. Thus, the production of basic industrial materials based on hydrogen, such as chemical inputs, cement or steel, is responsible for 18% of greenhouse gas emissions in Europe [Sartor and Bataille, 2019].

Decarbonizing this production by substituting clean technologies for polluting ones is one of the main challenges of developing a low-carbon hydrogen economy. It is also expected to decarbonize a wide range of sectors by opening hydrogen to new uses. As a replacement for fossil fuels, decarbonized hydrogen could clean up, for example, road transport or the building sector. In addition, by enabling energy storage, hydrogen could bring additional flexibility to energy networks, and so compensating for the variability of renewable energies.

Thus, decarbonized hydrogen seems to be driven by a proactive impetus from European governments. In July 2020, the EU published its "Hydrogen Strategy for a climate-neutral Europe", in which it sets ambitious targets for decarbonized hydrogen[1]. This momentum is shared by a growing number of Member States that are developing specific national strategies on this subject [FCH2JU, 2020]. In this context, most of them seem to focus their strategy on the development of electrolysis to decarbonize hydrogen production (a production noted PtH for "Power-to-Hydrogen"). Indeed, in line with the European Commission [2020], Member States seem to favor the emergence of electrolysis rather than Carbon Capture and Storage (CCS) methods combined with SMR[2]. However, if efforts have been made to support the research and development phase (R&D), thanks in particular to investment aids [3], few con-

[1] The EC has set targets of 6 GW of electrolyzer capacity by 2024 and 40 GW by 2030.

[2] In 2018, CCS methods accounted for only 0.7% of hydrogen production capacity, compared to 1.6% for electrolysis [Hydrogen Europe, 2020b], because the product purity level is better with electrolysis than SMR.

[3] These innovation aids are provided through the IPCEI, the Innovation Fund, the Horizon 2020 program or other nationally financed programs.

crete measures have been taken to develop massive production. Thus, according to Hydrogen Europe [2020b], current and planned projects for the development of electrolysis can only achieve 36% of the 2024 European objective and 23% of the 2030 one.

One of the main obstacles to this development is the lack of competitiveness of PtH hydrogen compared to production by SMR. In fact, the cost of hydrogen produced exclusively from renewable energies varies between 2.5 and 5.5€/kg, whereas the cost of SMR production is 1.5€/kg [European Commission, 2020]. According to the Hydrogen Council, economies of scale achievable in the production chain would allow 90% of the potential cost reductions of low-carbon hydrogen to be realized [Hydrogen Council, 2020]. This Council asserts that with the right policy framework[4], these costs could fall to between €1.4 and €2.3/kg by 2030 [Hydrogen Council, 2021]. Thus, these savings on low-carbon hydrogen will not be sufficient to achieve cost competitiveness without an effective carbon pricing system [RTE, 2020].

The appearance of high carbon or gas prices seems necessary to disqualify steam reforming production. As the price of gas is dependent on international markets, the only lever available to political governance seems to be the carbon price. However, according to Sartor and Bataille [2019], it turns out that the instability and the relatively low level (until recently[5]) of the carbon price in the European Emissions Trading System (EU-ETS) do not allow sufficient signaling for the commercialization of disruptive technology products. To remedy this, they study the theoretical benefits of using a Carbon Contract for Difference (CCfD).

The CCfD is a policy tool first described by Helm and Hepburn [2005]. It is a contract that assures the investor of a fixed carbon price by committing the public decision-maker to pay a certain amount corresponding to the production cost difference between the low-carbon technology and the reference one if the market carbon price is less than the fixed one. If the market price is higher than the fixed one, the government is reimbursed. Many theoretical advantages of this measure are highlight by the literature. First of all, thanks to an allocation through a bidding system, the CCfD is technologically neutral, which avoids the biases of a targeted incentive [Helm and Hepburn, 2005]. Then, thanks to an analytical model integrating investors' risk aversion, Richstein [2017] demonstrates that CCfD reduces the risks weighing on the project's revenues and thus reduces financing needs. This would allow innovation projects to overcome the "valley of death" [6], after the R&D phase. Rich-

[4] The Hydrogen Council recommends that governments implement measures consistent with their national strategy. For example, incentives for consumption and the development of new uses would support economies of scale.

[5] The price of CO_2 futures on the carbon market crossed €50 per ton on May 4, 2021, so Sartor and Bataille [2019] findings from 2019 should be viewed with caution.

[6] This is an expression used to describe the failure of the development of innovation projects after a phase of R&D subsidized by public aid.

stein and Neuhoff [2020] extend this reasoning by demonstrating the CCfD also reduces the necessary carbon price for investment in the project. The contract also reduces uncertainty about carbon price fluctuations due to temporal inconsistency in government strategies. In a mutually beneficial situation, the government agrees to tie its hands through the contract, which imposes a negative trade-off if it decides to lower the carbon price [Chiappinelli and Neuhoff, 2020]. The government, on the other hand, benefits from the contract since it allows for efficient financing per ton of decarbonized emissions with possible returns if the price of carbon increases above the fixed price. Thus, the cost of this policy would be only a small part of the public financing of the energy transition [Sartor and Bataille, 2019]. In the same vein, these authors, in their study of the effectiveness of CCfDs for the decarbonization of basic industrial materials, support the possibility of rapid and effective implementation of this measure, unlike the other policies studied. Indeed, to decarbonize the industry, the introduction of a price floor or border adjustments are proposed. However, in the short term, it is not politically feasible to implement them convincingly, unlike CCfDs, which can be effective even on a national scale.

The use of CCfD in the specific case of hydrogen electrolysis development has not, to our knowledge, been studied, yet it seems this tool could be adapted to it. Talebian et al. [2021] are interested in the effectiveness of existing or potential policies [7] targeting the development of the light hydrogen vehicle production chain in British Columbia, according to environmental and economic criteria. Adopting a multi-period and spatial cost-minimization model[8], they find that there is insufficient demand to support large-scale production from central electrolysis or carbon capture and storage (CCS), regardless of the level of hydrogen vehicle penetration. While measures are needed to develop this chain, the authors show that the most effective policies in this area are subsidies for operating costs (OPEX), ahead of investment subsidies and a ban on SMR production. In this context, CCfDs can be considered as a subsidy to OPEX since they reduce operating cost risks. Thus, Richstein and Neuhoff [2020] emphasize the relevance of CCfDs in the case where there is also a risk on the technology operating cost. It can correspond to the situation of hydrogen production by electrolysis, since it relies on electricity prices, known to be highly variable.

Indeed, as electricity prices are formed on the spot markets, they equalize the marginal costs of the last generation unit called. Depending on the load requested, these costs can correspond to those of coal or gas-fired power plants, which therefore include the carbon price. This is why the PtH cost in Europe can be more affected by the increase in the carbon

[7] The model considers the two policies currently in place in British Columbia, the LCFS and a carbon tax, as well as potential additional policies such as a ban on steam reforming production and subsidies for electrolytic production or carbon capture and storage (CCS).

[8] H2SCOT is a mixed integer linear model.

price than the SMR one [RTE, 2020]. This carbon price indirect effect on PtH production and the low pollution cost for SMR producers due to free allowances are two barriers to the effectiveness of the carbon price in the sector.

The implementation of a CCfD for the development of low-carbon hydrogen would complement the ETS system whose current design does not allow electrolysis to be competitive with steam reforming. Thus, the objective of this study is to analyse the conditions allowing the implementation of an economically efficient CCfD to support PtH competitiveness. Specifically, we define the CCfD strike and payment. We show there can be multiple threshold prices defining the strike and not just one as suggested by, for example, Sartor and Bataille [2019] and Richstein and Neuhoff [2020]. Since the value of the strike is impacted by the price of electricity, we invite characterizing the CCfD according to the power mix of each implementation region.

The section 2 is devoted to contract modeling to determine the appropriate contract "strike"[9] and payment for hydrogen development. The most efficient CCfD, i.e. the lowest cost contract allowing for an equivalence of the marginal costs of hydrogen production between SMR and electrolysis, is determined for each ETS market design. These marginal costs are a function of the price of gas and carbon for the steam reforming technology and the price of electricity for the electrolysis technology. Electricity prices are a function of carbon price and the marginal cost (fuel cost) of the last production unit called. Thus, using different data sources [CRE, 2010–2019, RTE, 2016], an estimation of marginal costs allows us to determine the characteristics of French and German CCfDs in the section 3. Finally, we conclude this study with its implications for policy makers.

2 Methodology

2.1 General framework

2.1.1 A price competition

Let us consider n firms producing a homogeneous good: hydrogen. These firms can be classified into two groups according to their production technology. The first is the group of hydrogen producers by steam reforming whose production marginal cost is c_s. The second is the group of hydrogen producers by electrolysis with a production marginal cost c_e. For simplicity, we consider that the firms bear the same costs for transport, storage and

[9]The optimal strike for the contract is the set of threshold carbon prices at which electrolytic hydrogen could be competitive with SMR hydrogen.

purification of hydrogen. This assumption corresponds to the situation in which hydrogen is produced at the site of consumption[10], for example as an input for industries. Firms compete on price in a single period and each group is able to satisfy the entire market demand[11], noted $D(p_h)$ where p_h is the hydrogen price.

Since the goods produced are homogeneous, with no spatial differentiation, consumers buy from the firm that offers the lowest price. We assume that if several firms offer the lowest price, then they share the market equally. As a result, demand for firm i ($i = 1, \dots, n$) is written as

$$D_i(p_{h_i}, p_{h_{-i}}) = \begin{cases} D(p_{h_i}) & \text{if } \forall j \neq i, p_{h_i} < p_{h_j}, \\ \frac{D(p_h)}{m+1} & \text{if } p_{h_i} = \min_{j=1,\dots,n}(p_{h_j}), \\ 0 & \text{if } \exists j \text{ such as} p_{h_i} > p_{h_j}, \end{cases} \tag{2.1}$$

where $-i$ represents all firms other than i, $m < n$ the number of firms offering the same price as i. Thus, the i firm profit is

$$\Pi_i(p_{h_i}, p_{h_{-i}}) = (p_{h_i} - c_i) D_i(p_{h_i}, p_{h_{-i}}), \tag{2.2}$$

where $c_i = c_e$ (respectively $c_i = c_s$) if i uses electrolysis (respectively steam reforming) technology.

Each firm sets its price under the assumption that its competitors will maintain their price regardless of what it chooses (Cournot conjecture). Decisions are made simultaneously. The Nash equilibrium is the n-tuple $(p^\star_{h_1}, \dots, p^\star_{h_i}, \dots, p^\star_{h_n})$ such as for all i, $p^\star_{h_i} = \arg\max_{p_{h_i}} = \Pi_i(p_{h_i}, p^\star_{h_{-i}})$. With a *reductio ad absurdum*, we can demonstrate the only Nash equilibrium is $p^\star_{h_i} = c_i$.

2.2 The use of CCfDs for competitive low-carbon hydrogen

Under the (realistic) assumption that the SMR marginal cost is lower than the PtH one, the hydrogen market price is equal to the SMR marginal cost. In this case, production by electrolysis is not profitable. However, these costs are functions of the carbon price. Consequently, a potential solution for low-carbon hydrogen (i.e. electrolysis technology) to be competitive is the implementation of a CCfD whose objective is to cover the difference between SMR and PtH marginal costs and not the investments in electrolysers. Thus, the

[10]This production of hydrogen on the site of consumption, called captive, is the most widespread since it represents 2/3 of the total production. The rest of the production is divided between the market production and the by-product in the industrial processes [Hydrogen Europe, 2020b].

[11]i.e. there are no production capacity constraints.

long-term constants are not integrated in the CCfD modeling, which focuses on marginal costs. The investment costs could be covered, upstream, by dedicated subsidies as detailed in the introduction.

CCfDs are long-term contracts[12] that depend only on carbon prices. Consequently, whoever develops this type of contract for the hydrogen industry should make assumptions about gas and electricity prices and consider "reference" prices (e.g. the expectation of gas and electricity prices over the contract duration). However, knowing that the electricity price at a given time t is the marginal cost of the last means of production called upon, which can be a function of carbon prices[13], the party who draws up the contract should not make assumptions on electricity prices but on the prices of the fuels needed to produce it, as well as on the yields of the power plants and their number of hours of operation to satisfy demand. To simplify our analysis, we assume that the reference prices, the efficiency of the technologies and their emission factors are known and constant over the duration of the CCfD. The only uncertainty considered is that of the carbon price. Given the construction of a CCfD, the only (temporal) variable of this contract is the carbon price. Consequently, to simplify the writing, we omit the time t in our equations.

2.3 Marginal cost specification

The marginal cost of hydrogen production by **SMR** (c_s) is a function of the gas price (p_g), the technology efficiency (rho_s), the CO_2 emission factor (e_s) and the CO_2 price on the ETS, which is

$$c_s(\sigma, p_g) = p_g\rho_s + e_s\sigma. \tag{2.3}$$

Vaporformers can receive free allocations of emission permits (current situation). These subsidies reduce their marginal cost of CO_2 emissions like a unit subsidy. Therefore, if we note $a \in [0; e_s]$ this unit subsidy, the marginal cost of production of the steam reforming technology can be rewritten as

$$c_s^a(\sigma, p_g) = p_g\rho_s + (e_s - a)\sigma. \tag{2.4}$$

[12] Sartor and Bataille [2019] suggest a duration of 5 to 10 years and Richstein and Neuhoff [2020] a duration of 3 to 20 years.

[13] The means of electricity production are called by order of merit, i.e. by increasing order of marginal costs. Thus, if for a given time t the last production unit called to satisfy the demand is a gas power plant with an efficiency of ρ and an emission factor of ϵ, the price considered will be equal to $\frac{p_g}{\rho} + \epsilon\sigma$ where p_g is the gas price and σ is the carbon one.

The marginal cost of hydrogen production by **electrolysis technology** (c_e) is a function of its efficiency (ρ_e) and the electricity price (p_e). However, as previously mentioned, the latter depends on the market carbon (σ) and fuel prices. Thus, we set

$$c_e(\sigma, p_g) = p_e(\sigma, p_g)\rho_e, \tag{2.5}$$

$$p_e(\sigma, p_g) = p_0 + p_1\sigma + p_2\sigma^2 + p_3 p_g, \tag{2.6}$$

where $p_0 \geqslant 0$, $p_1 > 0$, $p_2 < 0$ et $p_3 \geqslant 0$.

These parameters depend on the electricity mix and demand of the considered region. A double effect of the carbon price on the electricity price is represented: on the one hand, a direct positive cost linked to the internalization of pollution costs and on the other hand, an indirect effect, this time negative, caused by the adaptation of the fleet to these costs (represented by the parameter p_2). Since gas prices impact the marginal cost of SMR production and may impact the electricity price, we isolate it from the prices of other fuels in the specification of the electricity price function (2.6). The value and meaning of the parameters p_0 and p_3 depend on the type of price considered. Thus, if it is an hourly price and if during the hour the marginal technology is a gas plant (respectively coal) then $p_0 = 0$ and p_3 is the inverse of the plant efficiency (respectively p_0 equals the coal price divided by the plant efficiency and $p_3 = 0$). If the price considered is annual (resp. multi-annual), then p_3 is the percentage of hours when the gas technology is marginal during the year (resp. all years) divided by the efficiency of this technology, and p_0 is a weighted average over the year (resp. all years) of the marginal costs of the coal, fuel oil and nuclear technologies.

The indirect effects of the price of CO_2 on the production costs of PtH, defined by $c_e(\sigma) - c_e(0)$, can be offset by unitary subsidies[14] noted $\chi \in [0; 1]$. Taking into account these subsidies, the marginal cost of production of this technology is rewritten as

$$c_e^{\chi}(\sigma, p_g) = c_e(\sigma, p_g) - \chi(c_e(\sigma, p_g) - c_e(0, p_g)). \tag{2.7}$$

Remark 2.1. *If $\chi = 0$ this is the situation where there is no offsetting (current situation). In the following, we assume that $\chi \neq 1$, in coherence with the regulation*[14].

[14] The revised ETS state aid guidelines for the period after 2021 include hydrogen as a sub-sector at risk of carbon leakage. As such, it can benefit from a unit offsetting of up to 75% of the indirect costs of its emissions.

2.4 Determination of the CCfD strike and payment

The purpose of the CCfD is to compensate for the market price of CO_2, which is not efficient for the development of decarbonized hydrogen, and not to supplement the market prices of inputs (gas, electricity). Its payment at a time t varies according to the difference between a price fixed by the contract, called strike, and the market carbon price at that time.

The strike is the set of positive CO_2 prices such that the marginal production costs of the two technologies are equal. Thus, if we note $\gamma^{\chi,a}(\sigma, p_g)$ the difference between the two production marginal costs i.e.

$$\gamma^{\chi,a}(\sigma, p_g) = c_e^{\chi}(\sigma, p_g) - c_s^a(\sigma, p_g), \tag{2.8}$$

the strike is defined by the solution(s) σ (where $\sigma \in \mathbb{R}$) of the quadratic carbon price equation

$$\gamma^{\chi,a}(\sigma, p_g) = 0. \tag{2.9}$$

Therefore, contrary to our knowledge of the literature [e.g. Sartor and Bataille, 2019, Richstein and Neuhoff, 2020], there may be several carbon prices defining the strike. According to our hypothesis, $\gamma^{\chi,a}$ in a concave function of the CO_2 price[15]. It is decreasing (respectively increasing) in the gas price if ρ_e is lower (resp. higher) than $\frac{\rho_g}{p_3}$[16]. It is decreasing with the efficiency of the SMR technology and increasing with the efficiency of the electrolysis technology.

Since the strike is fixed, the gas price p_g considered in the following is a constant reference price over the contract period. The equation 2.9 solutions number depends, among other things, on the value of this price. Thus, we can state the Proposition 2.2.

Proposition 2.2. *Let's denote $\bar{p}_g^{\chi,a}$ the gas price that cancels the discriminant of the polynomial 2.9, therefore*

$$\bar{p}_g^{\chi,a} = -\frac{(e_s - a)^2 - 2p_1(e_s - a)\rho_e(1-\chi) + \rho_e^2(p_1^2(1-\chi) - 4p_0p_2)(1-\chi)}{4p_2\rho_e(\rho_g - p_3\rho_e)(1-\chi)}. \tag{2.10}$$

As a result,

1. *If $p_g > \bar{p}_g^{\chi,a}$ then for all σ, $\gamma^{\chi,a}(\sigma, p_g) < 0$ i.e. whatever the carbon price, the SMR*

[15] Indeed, from (2.5)–(2.4), we have $\frac{\partial \gamma^{\chi,a}(\sigma,p_g)}{\partial \sigma} = \rho_e(p_1 + 2p_2\sigma)(1-\chi) - (e_v - a)$ and $\frac{\partial^2 \gamma^{\chi,a}(\sigma,p_g)}{\partial \sigma^2} = 2p_2\rho_e(1-\chi) < 0$.

[16] Indeed, $\frac{\partial \gamma^{\chi,a}(\sigma,p_g)}{\partial p_g} = p_3\rho_e - \rho_g$.

technology is more expensive than the electrolysis technology. In this case, there is no need to set up a CCfD.

2. *If $p_g = \bar{p}_g^{\chi,a}$, then the equation 2.9 has a solution, noted $\bar{\sigma}^{\chi,a}$. Whatever the carbon price, SMR is more expensive than electrolysis[17]. As a result, the CCfD is inefficient in this case.*

3. *If $p_g < \bar{p}_g^{\chi,a}$ then there are two carbon price thresholds, $\bar{\sigma}_m^{\chi,a}$ and $\bar{\sigma}_M^{\chi,a}$, such as if the market carbon price is included in this interval then the PtH marginal cost is higher than the SMR one. Therefore, the implementation of a CCfD could make low-carbon hydrogen competitive.*

The analytical expressions of the equation 2.9 solutions are

$$\bar{\sigma}^{\chi,a} = \frac{(e_s - a)}{2p_2\rho_e(1-\chi)} - \frac{p_1}{2p_2}, \tag{2.11}$$

$$\bar{\sigma}_m^{\chi,a} = \bar{\sigma}^{\chi,a} - \frac{\Gamma_1}{\Gamma_2}, \tag{2.12}$$

$$\bar{\sigma}_M^{\chi,a} = \bar{\sigma}^{\chi,a} + \frac{\Gamma_1}{\Gamma_2}, \tag{2.13}$$

where

$$\Gamma_1 = \sqrt{(e_s - a - p_1\rho_e(1-\chi))^2 + (4p_2\rho_e(-p_0\rho_e + p_g(\rho_g - p_3\rho_e)))(1-\chi)}, \tag{2.14}$$

$$\Gamma_2 = -2p_2\rho_e(1-\chi). \tag{2.15}$$

Thus, we get the following properties

- $\bar{\sigma}_m^{\chi,a} < \bar{\sigma}_M^{\chi,a}$ and $\frac{\partial \bar{\sigma}_m^{\chi,a}}{\partial p_g} = -\frac{\partial \bar{\sigma}_M^{\chi,a}}{\partial p_g}$,
- If ρ_e is less (resp. greater) than $\frac{\rho_g}{p_3}$ then $\sigma_m^{\chi,a}$ is increasing croissant (resp. decreasing) and $\sigma_M^{\chi,a}$ is decreasing (resp. increasing) in p_g,
- If $e_s - a \geqslant p_1\rho_e(1-\chi)$ then $\bar{\sigma}^{\chi,a} \leqslant 0$ and $\bar{\sigma}_m^{\chi,a} < 0$ and for all $p_g \leqslant \frac{p_0\rho_e}{\rho_g - p_3\rho_e}$ there is $\bar{\sigma}_M^{\chi,a} \geqslant 0$,
- If $e_s - a \geqslant p_1\rho_e(1-\chi)$ ads $p_g > \frac{p_0\rho_e}{\rho_g - p_3\rho_e}$, then $\bar{\sigma}_M^{\chi,a} < 0$,
- If $e_s - a \leqslant p_1\rho_e(1-\chi)$ then $\bar{\sigma}^{\chi,a} \leqslant 0$ and $\bar{\sigma}_m^{\chi,a} < 0$ and for all $p_g \leqslant \frac{p_0\rho_e}{\rho_g - p_3\rho_e}$ there is $\bar{\sigma}_m^{\chi,a} \leqslant 0$,

[17] They are equal if $\sigma = \bar{\sigma}^{\chi,a}$.

- If $e_s - a \leqslant p_1\rho_e(1-\chi)$ and $p_g > \frac{p_0\rho_e}{\rho_g - p_3\rho_e}$ then $\bar{\sigma}_m^{\chi,a} > 0$,
- If $p_g < \bar{p}_g^{\chi,a}$ and if $\sigma \in]\bar{\sigma}_m^{\chi,a}; \bar{\sigma}_M^{\chi,a}[$ (as $p_2 < 0$) then $c_e > c_s$ or else $c_e \leqslant c_s$

Given these properties and Proposition 2.2, the following theorem, which defines the strike, can be stated.

Theorem 2.3. *The CCfD will be implemented only if the reference gas price (e.g. the expected value of the gas price over the term of the contract) is below a certain threshold ($\bar{p}_g^{\chi,a}$) and* ***the couple*** $(\bar{\sigma}_m^{\chi,a}, \bar{\sigma}_M^{\chi,a})$ ***constitutes the strike****.*

Thus, an optimal CCfD will not necessarily be defined from a single carbon price threshold [called strike by Sartor and Bataille, 2019, for instance] such that if the carbon price is below this threshold then the beneficiary of the contract receives a certain amount of money. Indeed, due to the specification of electricity price (input of PtH production) which is a quadratic function of carbon, we have highlighted the existence of two thresholds, i.e. a couple of carbon prices which constitute the strike. The CCfD payment formula, function of the selected strike, is defined in the Theorem 2.4.

Theorem 2.4. *If the reference gas price is less than $\bar{p}_g^{\chi,a}$, then in order to guarantee the competitiveness (in expectation) of the electrolysis technology compared to that of the steam-reforming technology, a CCfD can be proposed to the producers of hydrogen by electrolysis, the payment of which, noted $\bar{\gamma}^{\chi,a}$, is a function of market carbon prices (σ) and of the selected strike :*

$$\bar{\gamma}^{\chi,a}(\sigma) = \Gamma_1(\bar{\sigma}_M - \sigma) - \frac{\Gamma_2}{2}(\bar{\sigma}_M - \sigma)^2 = -\Gamma_1(\bar{\sigma}_m - \sigma) - \frac{\Gamma_2}{2}(\bar{\sigma}_m - \sigma)^2 \tag{2.16}$$

where Γ_1 is defined by (2.14) and Γ_2 by (2.15).

The CCfD's payment formula depends on electricity price parameters. However, these are linked, among other things, to the electricity production fleet, which differs from one country to another. Consequently, it is preferable to have CCfDs differentiated by country even if the hydrogen production technologies are identical from one country to another. We illustrate this point in the following section devoted to an analysis of the French and German cases.

3 Determination of French and German CCfDs

In this section, the optimal CCfDs for the development of hydrogen by electrolysis in France and Germany are determined. First, the data set used is detailed. Estimates of the electricity price function parameters (equation 2.6) are presented. Then, an analysis of the costs of hydrogen produced by the two technologies as a function of electricity, gas and carbon prices is performed. Finally, the contract strike and payment and their variations according to some parameters (e.g. subsidies granted) are characterized for France and Germany.

3.1 Data

3.1.1 Electricity price

The values we assigned to the parameters of the electricity price function (equation 2.6) were estimated from quarterly data for gas and electricity prices from the French Commission for Energy Regulation's Market Observatories [CRE, 2010–2019] from 2010 to 2019. For France (respectively Germany), these prices are averages of base and peak spot prices on the Powernext market (resp. European Energy Exchange). Therefore, under the hypothesis of a continuous hydrogen production, 24 hours a day, the average electricity price for a hydrogen producer by electrolysis is a weighted average of the base and peak prices of the market corresponding to the considered country. These electricity prices thus calculated constitute the observations of our explained variable (p_e). The observations for the carbon prices are front-year prices[18] from ICE Endex[19].

The ordinary least squares estimate results are available in appendix A. We summarize here the final results. We retain the following specification of the electricity function

$$p_e = p_1\sigma + p_2\sigma^2 + p_3 p_g + \epsilon, \tag{3.1}$$

where the values of the estimated parameters for France (respectively Germany) as shown in Table 1 (respectively in Table 2).

In this application, the parameter p_0 in equation (2.6) is not significant. A first explanation could be that, most of the time, the marginal technology in electricity production is a gas technology. A second possible explanation is that the influence of other marginal technologies (coal, fuel oil, etc.) is captured by the parameters associated with the carbon price p_1 and p_2.

We find that the value of the parameter associated with σ, i.e. p_1, is the same in France and in Germany (equal to 3.16). The impact of gas and electricity prices characterized by p_3, all else being equal, is more important in France (equal to 1.22) than in Germany (equal

[18] Since the CO_2 spot market is residual and the CO_2 futures and spot prices are linked by a cash and carry arbitrage relationship, we use these futures prices.

[19] C.f ICE Endex.

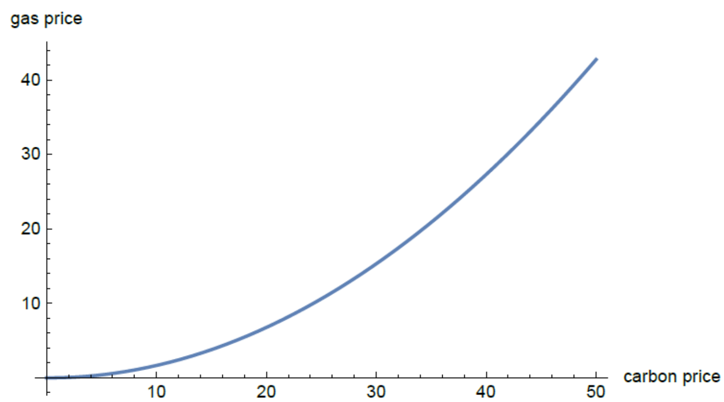
Explanatory var.	**Parameter**	Estimation	SD	t-value	$P(>\lvert t\rvert)$
p_g	p_3	1.22	0.18	6.64	2e-7
σ	p_1	3.16	0.78	4.05	0.000321
σ^2	p_2	-0.10	0.03	-2.83	0.008178

Table 1: Linear regression results for the French case.

Explanatory var.	**Parameter**	Estimation	SD	t-value	$P(>\lvert t\rvert)$
p_g	p_3	1.00	0.12	8.23	2.7e-9
σ	p_1	3.16	0.52	6.12	8.76e-7
σ^2	p_2	-0.08	0.02	-4.09	0.000285

Table 2: Linear regression results for the German case.

to 1). For any gas price greater than $(-0.0057 + 0.0172\sigma)\sigma$ the price of electricity in France is higher than in Germany (see Figure 1).



Interpretation: For a certain value of σ (in €/t) if the gas price (in €/MWh) is above this curve then the electricity price in France is higher than in Germany.

Figure 1: Gas price above which the electricity price in France is higher than in Germany

Note that if we consider only positive electricity prices, the specification 3.1 is only valid for certain values of the carbon price. Indeed, for a given gas price, p_g, to guarantee the positivity of the electricity price, the carbon price σ must be between $\max(0, \frac{p1-\sqrt{p_1^2-4p_2p_3p_g}}{-2p_2})$ and $\frac{p1+\sqrt{p_1^2-4p_2p_3p_g}}{-2p_2}$.

3.2 Other parameters

The benchmark values of the parameters, other than electricity prices, used in our numerical application to determine the strike and payment of CCfDs are defined in Table 3.

They were determined using data from Hydrogen Europe [2020a], Eurostat [2021] and RTE [2016].

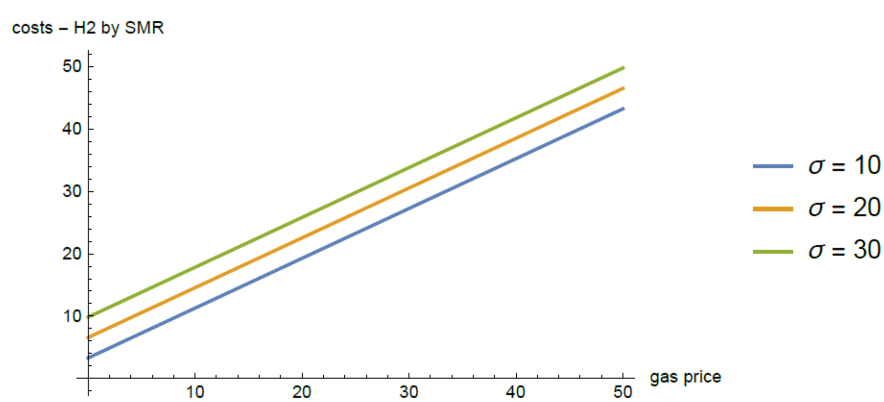
ρ_g	e_s	ρ_e	a	χ
80%	$0.328gCO_2/MWh$	50%	0	0

Table 3: Reference values of the model parameters.

3.3 Analysis of hydrogen production costs

In order to characterize the most efficient CCfDs for the French and German cases, the first step is to understand precisely the production costs of hydrogen according to the two technologies, since it is the difference between these two marginal production costs that needs to be compensated with the contract.

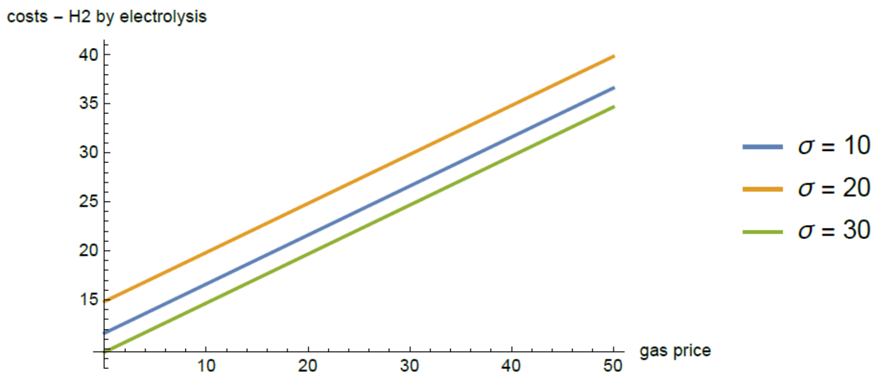
In general and independently of the studied region, SMR production marginal cost (2.4) is an increasing function of the gas price (where ρ_g is the grade) and of the CO_2 price (where $e_s - a$ is the grade). Figure 2 is an illustration.



Interpretation: The lines above represent the marginal costs of hydrogen production by SMR as a function of the gas price, for certain values of the carbon price, σ, when the efficiency of the technology ρ_g is 80%, the carbon emission factor e_s is 32.8% and without free allocation of carbon emission permits $a = 0$. These lines are increasing in gas price (slope of 0.8) and in carbon price (the lines are parallel and separated by a distance of $(a - e_s)|\sigma 1 - \sigma 2|$ where $\sigma 1$ and $\sigma 2$ are two different carbon prices).

Figure 2: Marginal costs of hydrogen by SMR as a function of gas price.

The case of electrolytic generation is slightly more sophisticated. If the parameter p_3 of the electricity price function (2.6) is non-zero[20] (case for France and Germany) then the PtH marginal cost (2.5) is strictly increasing with the gas price. Because of the indirect effects of CO_2, this marginal cost is a quadratic function of the carbon price. It is increasing for any $\sigma < -p_1/2p_2$ and decreasing for any $\sigma > -p_1/2p_2$. This is why, on Figure 3, the line for $\sigma = 10/\text{t}$ is between the lines $\sigma = 20$ and $\sigma = 30/\text{t}$.



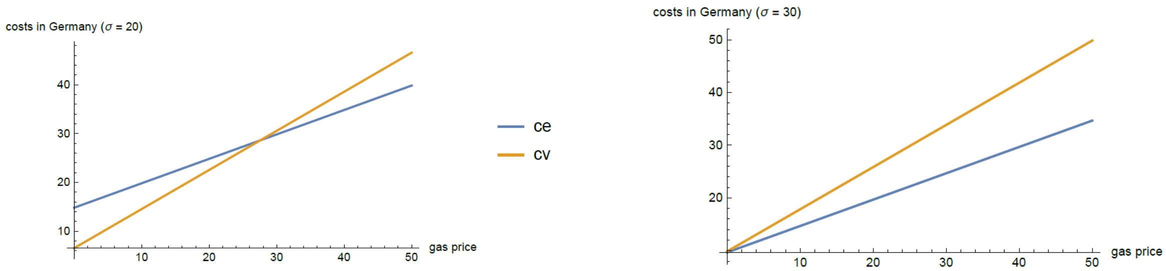
Interpretation: The lines above represent the PtH marginal costs in Germany as a function of the gas price when the technology efficiency ρ_e is 50% and without carbon offsetting ($\chi = 0$). These lines are increasing (resp. decreasing) if the price of carbon σ is less (resp. more) than 19.75€/t.

Figure 3: Marginal costs of hydrogen by electrolysis as a function of the price of gas.

Given the value of the selected parameters (Table 3), we assume that the SMR marginal costs (2.4) are the same in France and Germany (for the same gas price). Because of the differences in the electricity mix and the seasonality of the electricity demand between these two countries (i.e. different parameters of the electricity price function), it is also interesting to study the differences in production costs between these two countries. In Germany (Figure 4) as in France (Figure 5), for a high enough carbon price, electrolysis production is competitive with steam reforming production. Below this price, there is a threshold gas price for each country below which the cost of production by steam reforming is lower than the cost of production by electrolysis. For instance, in Germany and for a carbon price of 20€/t, a CCfD will allow to subsidize the competitiveness of electrolysis production for a gas price below 27.57€/MWh. Above this price, producers would pay back a certain amount to the government.

The carbon price evolution influences the competitiveness gap of hydrogen by electrolysis between France and Germany. Thus, while for $\sigma = 10$€/t, German production is less expensive than French production (for a gas price higher than or equal to 1.7€/MWh), for

[20]If $p_3 = 0$ then the marginal cost of hydrogen production by electrolysis is independent of the gas price.



Costs for a carbon price of 20€/t. Costs for a carbon price of 30€/t.

Interpretation: The blue (respectively orange) curves represent, as a function of the gas price (€/MWh), the marginal costs of hydrogen production by electrolysis (resp. steam reforming) in Germany (i.e. for parameters whose values are those of Tables 2 and 3, when the carbon price is 20€/t (left figure) and 30 €/t (right figure). If the carbon price is 20€/t then for any gas price below 27.57€/MWh the marginal cost of electrolysis production is higher than that of steam reforming production. When the carbon price is 30€/t, for any (positive) gas price, the marginal costs of steam reforming production are higher than those of electrolysis.

Figure 4: Costs of both technologies in Germany.

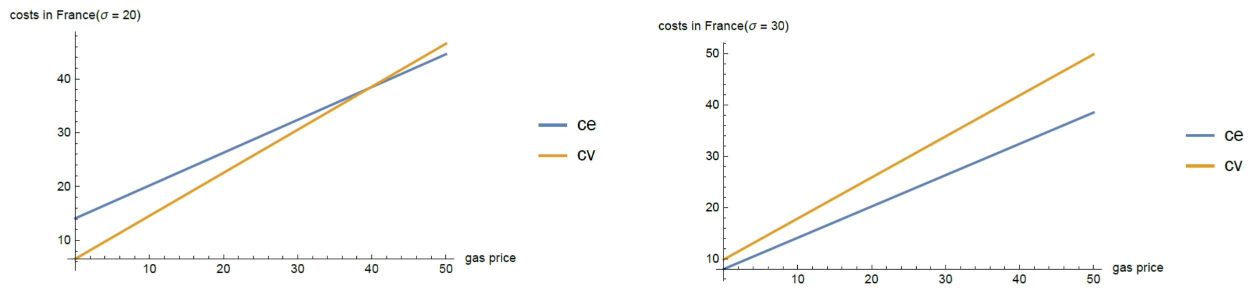
σ = 30€/t, the trend can be reversed according to the gas price (see Figure 6). There is a threshold gas price (function of σ)[21] such that, for any gas price above this threshold, the electrolysis production technology is more expensive in France than in Germany. In general, if we consider two countries A and B whose electricity price function parameters are $p_0 = 0$, $p_1 = p_{1i}$, $p_2 = p_{2i}$ and $p_3 = p_{3i}$ for $i = A$ or B, then if the gas price is greater (resp. less) than $\frac{\sigma(p_{1B}-p_{1A}+(p_{2B}-p_{2A})}{p_{3A}-p_{3B}}$ it is more expensive (resp. less expensive) to produce hydrogen by electrolysis in country B than in country A.

3.4 Analysis of the CCfD's price and payment

3.4.1 CCfD characteristics without additional State aid

As noted earlier, the existence of distinct electricity prices across generation assets leads to regionally specific CCfDs, as illustrated in Figure 4. In this figure, electrolysis production is more expensive than SMR production within the curves. Also, for a given gas price, the government would make a payment to electrolytic hydrogen producers when the CO_2 price is in the range $[\sigma_m; \sigma_M]$ and *vice versa*. From Proposition 2.2, the CCfD is only useful if the gas price is below a certain threshold equal to 47.20€/MWh for France and 31.15€/MWh for Germany. Given the value of the electricity price parameters, the area corresponding to a subsidy of the electrolysis production is wider in France than in Germany.

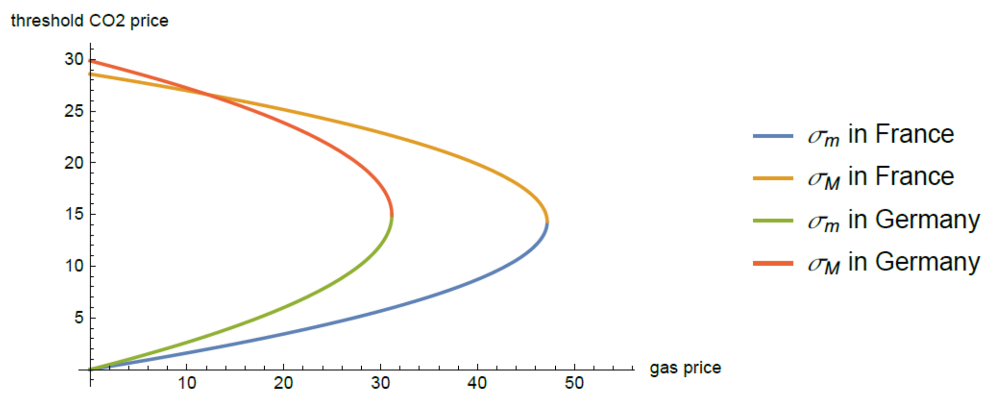
[21] According to the selected parameters values, this threshold price is $(-0.00571 + 0.0172\sigma)\sigma$.



Costs for a carbon price of 20€/t. Costs for a carbon price of 30€/t.

Interpretation : The blue (respectively orange) curves represent, as a function of the gas price (€/MWh), the marginal costs of hydrogen production by electrolysis (resp. SMR) in France (i.e. for parameters whose values are those of the Tables 1 and 3 when the carbon price is 20€/t (left figure) and 30 €/t (right figure). If the carbon price is 20€/t then for any gas price below 39.67€/MWh the marginal cost of electrolysis production is higher than that of steam reforming production. When the carbon price is 30€/t, for any (positive) gas price, the marginal costs of the steam reforming production are higher than the electrolysis production.

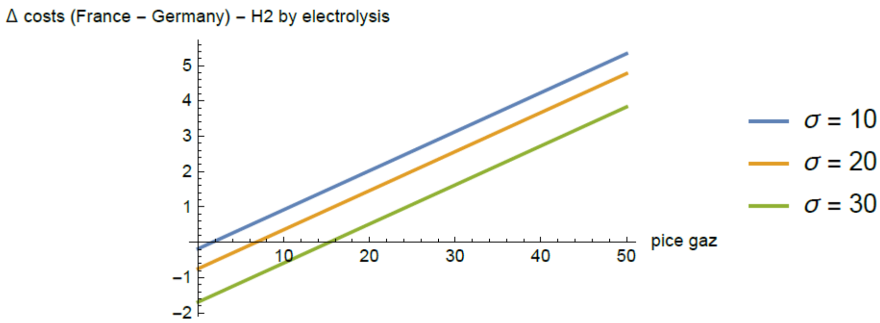
Figure 5: Costs of both technologies in France.



Interpretation: The curves above represent the strike of the French and German CCfDs as a function of the gas price. More precisely, the couple $(\sigma_m;\sigma_M)$ for both countries. We see that for any gas price below 12€/MWh, the French σ_M is lower than the German one. For any positive gas price the French σ_m is lower than the German one. The abscissa of the connection point of the σ_m and σ_M curves corresponds to $\bar{p}_g^{\chi,a}$ defined in (2.10) i.e. the gas price above which the CCfD is useless. It is equal for France to 47.19€/MWh and for Germany to 31.15€/MWh. For any pair (p_g,σ) inside the curves the payment to the producer is positive.

Figure 7: CCfD strikes in France and Germany.

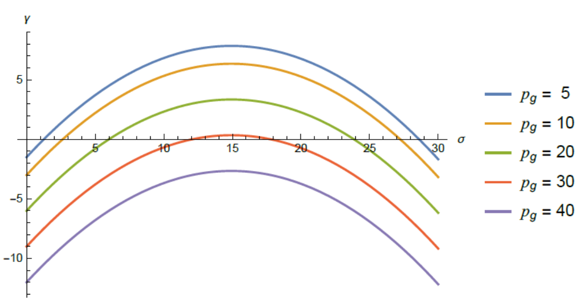
Therefore, for an equal CO_2 price on the market, the payments made by the government to producers can be higher in France than in Germany, as illustrated in Figure 8. For example, for a gas price of 30€/MWh, the payment is slightly positive in Germany for a market carbon price between 12 and 17€/t, while in France it is largely positive for a price between 6 and 23€/t. As a reminder, when the payment is negative, it is a form of reimbursement made by



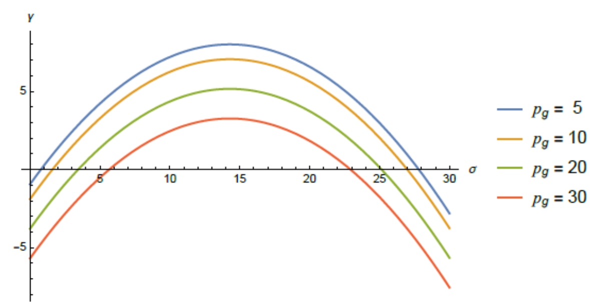
Interpretation: The above curves represent the difference between the marginal costs of hydrogen production by electrolysis in France and Germany as a function of the gas price (€/MWh) and for three values of the carbon price (in €/t) (given the values of the parameters in Tables 1 to 3). We can see that if the carbon price is 20€/t, then for any gas price higher than 6.77€/MWh, hydrogen production by electrolysis is more expensive in France than in Germany.

Figure 6: Difference in marginal costs of hydrogen production by electrolysis between France and Germany.

the electrolysis hydrogen producers to the government. Also, Figure 8 illustrates the non-monotonicity of the payment function and highlights the existence of a gas price at which the payment is negative regardless of the carbon price. This threshold gas price $\bar{p}_g^{\chi,a}$ is defined in (2.10) and calculated previously (see Figure 4 for example).



CCfD payment in Germany.



CCfD payment in France.

Interpretation: The curves represent the payment of the German CCfD (left curves) and the French CCfD (right curves) as a function of the carbon price (€/t) and according to different values of the gas price (€/MWh). For a gas price of 40€/MWh the German CCfD payment is always negative since $\bar{p}_g^{\chi,a} = 31.15€/MWh$ in Germany. For this gas price of 40€/MWh the CCfD is useless. For any gas price below the threshold price $\bar{p}_g^{\chi,a}$ the payment is negative if the carbon price is below σ_m or above σ_M and positive otherwise.

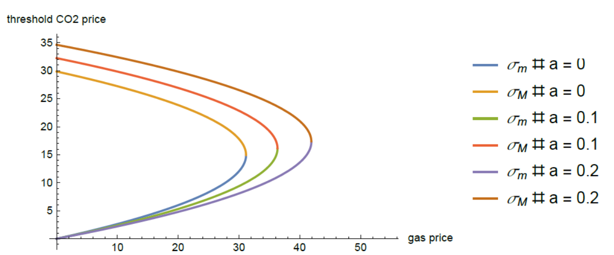
Figure 8: CCfD payment in France and Germany according to the carbon price on the market.

Example. Suppose that the CCfD developer estimates that, over the contract period, the gas price will be 20€/MWh. Given the electricity price specification (3.1), this is only valid in France (resp. Germany) for a carbon price below 38.02€/t (resp. 45.05€/t). The strikes (in €/tCO_2) are for France $(3.44; 25.14)$ and for Germany $(6; 23.87)$. The payment function of the French CCfD is $0.95(25.14-\sigma)-0.044(25.14-\sigma)^2$ or equivalently $-0.95(3.44-\sigma)-0.044(3.44-\sigma)^2$ and that for Germany $0.75(23.87-\sigma)-0.042(23.87-\sigma)^2$ or equivalently $-0.75(6-\sigma)-0.042(6-\sigma)^2$. We omit in this study issues related to the duration of the contract. This essentially influences the determination of parameter values (yields, reference input prices, etc.).

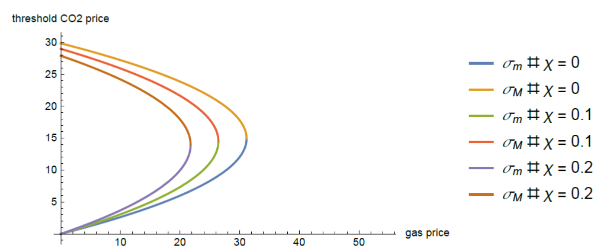
3.5 Impacts of state aid supplementing the ETS

As a reminder, the developed model allows the study of two state aids complementing the ETS market: carbon offsetting for PtH (χ) and free allocations for SMR (a).

Unsurprisingly, as illustrated in Figures 9 and 10, carbon indirect effect offsets lower the threshold price needed for an efficient contract. Conversely, the strikes are increasing with free allocations. Thus, to reduce the costs associated with the implementation of CCfD for public policy makers, it would be possible to increase carbon offsetting or to decrease free allocations.



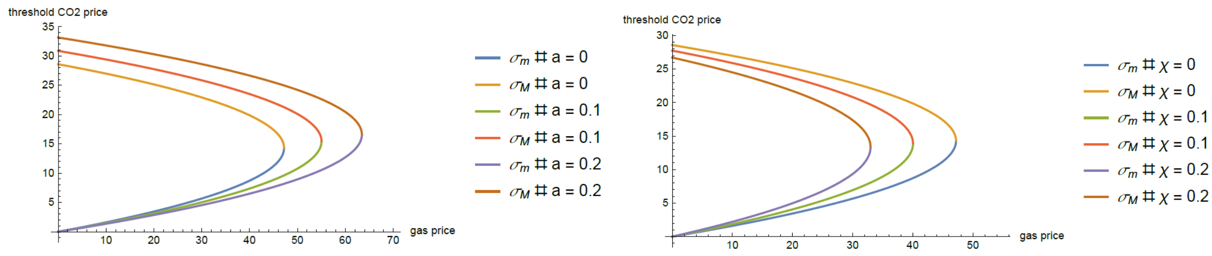
Impact of free allowances for SMR.



Impact of carbon offsetting for electrolysis.

Interpretation: The above curves represent the changes in the strike (in €/t) as a function of the gas price (in €/MWh), following free allocations of emission permits for steam reforming (left) and indirect carbon offsets for electrolysis (right).

Figure 9: Impacts of the subsidies supplementing the carbon market on the CCfD strike in Germany.



Impact of free allowances for SMR. Impact of carbon offsetting for electrolysis.

Figure 10: Impacts of the subsidies supplementing the carbon market on the CCfD strike in France.

4 Conclusion

This study focused on characterizing an efficient CCfD for the commercial development of decarbonized hydrogen. Our analysis focuses on the marginal cost differential between SMR and PtH technologies. Omitting storage, purification, and transportation costs, we focus only on hydrogen produced at the site of its consumption, primarily for industrial use.

We determine a threshold gas price at which, whatever the carbon price, hydrogen produced by electrolysis is cheaper than that produced by steam reforming. In the case where this threshold price is exceeded, the CCfD is not efficient since it would substitute the inputs market prices. This result has two main implications. First, future gas price developments should be taken into account when defining the duration of the CCfD. On the other hand, it would be necessary to ensure that the gas price is below this threshold in each region where the CCfD could be implemented. This brings us to the second main conclusion, which concerns the countries of implementation of the CCfD. Given the sensitivity of the model to electricity prices (i.e. electricity mixes and seasonality of electricity demands) it seems important to characterize different CCfDs for each generating fleet. This result invites us to advise against the implementation of a single CCfD for the whole European Union, which is considered economically inefficient due to the variety of parks existing in this area. This conclusion could be reconsidered in the hypothesis of the existence of a single electricity price in Europe, as studied in the annex. Finally, the current policies complementing the EU-ETS market do not seem to prevent the implementation of CCfD. However, reducing free allocations for steam reforming or increasing carbon offsetting for electrolysis could improve the effectiveness of the tool for the development of decarbonized hydrogen. In any case, these additional aids must be taken into account in the definition of the CCfD since they impact the form of the Contract strike and payment.

To complete our analysis, a multi-period model could be developed to integrate investment decisions. The complementary aids to the development of the electrolysis sector could thus be studied. Taking into account the cost of transport and storage would allow us to extend the analysis and consider other hydrogen consumers.

The study of CCfD characteristics could also be completed in the following two ways. On the one hand, a larger empirical study could test the validity of the values obtained and their sensitivity to variations in the parameters of the variable cost functions. On the other hand, assessing the environmental impact of this policy in terms of avoided emissions would ensure the effectiveness of the CCfD as a complement to the EU-ETS market.

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Appendices

A Detailed econometric study for the electricity price function in France and Germany

As a reminder, this study is based on data from the French "Commission de Régulation de l'Energie" published quarterly in CRE [2010–2019].

The results of the parameter estimates of the electricity price function (2.6) for France and Germany are given in tables 4 and 5.

Explanatory var.	Estimation	SD	t-value	$P(>\|t\|)$
p_0	13.723	9.11	1.51	0.14
p_g	0.99	0.32	2.88	0.01
σ	2.25	1.37	1.64	0.11
σ^2	-0.06	0.05	-1.22	0.23

$R^2 = 0.3235$, adjusted $R^2 = 0.26$, p-value < 0.005355

Table 4: Results of the linear regression for the French case with constant.

Explanatory var.	Estimation	SD	t-value	$P(>\|t\|)$
p_0	3.58	5.28	0.68	0.50
p_g	0.92	0.18	5.00	1.98e-05
σ	2.99	0.79	3.76	0.0007
σ^2	-0.08	0.03	-2.71	0.0107

$R^2 = 0.6658$, adjusted $R^2 = 0.6345$, p-value = 9.24e-08

Table 5: Results of the linear regression for the German case with constant.

Since the constant is not significant for the French and German cases, we have removed it from the specification of the electricity price used to determine the main characteristics of the CCfD. This significantly improves the significance of the model and of each of the parameters, as can be seen in the tables 6 and 7.

In order to verify the viability of the models and their estimates, we perform a series of tests, the results of which are presented in the Table 8[22].

The Saphiro-Wilk test, which was chosen because of the small sample, does not confirm the hypothesis of normality of the residuals for the French case. However, the Breusch-Pagan test does not reject the hypothesis of the residuals homoscedasticity. We therefore

[22] p-v = p-value.

Explanatory var.	Estimation	SD	t-value	$P(>\|t\|)$
p_g	1.21	0.25	4.76	3.71e-05
σ	3.57	1.07	3.32	0.00219
σ^2	-0.11	0.04	-2.52	0.01692

Table 6: Results of the linear regression for the French case without constant.

Explanatory var.	Estimation	SD	t-value	$P(>\|t\|)$
p_g	0.995	0.14	6.96	5.93e-08
σ	3.33	0.66	5.50	4.2e-06
σ^2	-0.09	0.02	-3.84	5.29e-04

Table 7: Results of the linear regression for the German case without constant.

check for skewness and kurtosis: the results of the Kurtosis test invite us to check for the presence of outliers. We notice, with the residuals plot (Figure 1), that points 26 and 27 are atypical. These points correspond to the 2016–2017 winter, the coldest winter the region has experienced in over 100 years. Because of the high electricity demand during this period, coal played a larger role in defining electricity price than in other quarters. Because our electricity price specification does not specifically account for the influence of this generating unit, we removed these points from our database.

With this new database, we obtain the results presented in Tables 9 and 10, which are better than before according to the coefficients significance and prediction. The residuals tests for the electricity price specification (2.6) with $p_0 = 0$ do not reject the normality hypotheses (Table 11) in the French and German cases. We use this specification for electricity prices in France and Germany in the section 3, with the parameter values provided in Tables 9 and 10.

test	France	Germany
Shapiro-Wilk	p-v = 0.001	p-v = 0.77
Breusch-Pagan	0.59	p-v = 0.39
Skewness	T=1.40 ; p-v = 0.002	T = 0.16 ; p-v = 0.67
Kurtosis	T = 5.10 ; p-v = 0.01	T= 3.65 ; p-v = 0.32

Table 8: Results of the residue tests for the French and German cases, with the complete database.

Explanatory var.	Estimation	SD	t-value	$P(>\|t\|)$
p_g	1.22	0.18	6.64	2e-7
σ	3.16	0.78	4.05	0.000321
σ^2	-0.10	0.03	-2.83	0.008178

Table 9: Linear regression results for the French case, without constant and without winter 2016-2017.

Explanatory var.	Estimation	SD	t-value	$P(>\|t\|)$
p_g	1,00	0,12	8,23	2,7e-9
σ	3,16	0,52	6,12	8,76e-7
σ^2	-0,08	0,02	-4,09	0,000285

$R^2 = 0.9897$, adjusted $R^2 = 0.9887$, p-value $<$ 2,2e-16

Table 10: Linear regression results for the German case, without constant and without winter 2016-2017.

test	France	Germany
Shapiro-Wilk	p-v = 0.19	p-v = 0.66
Breusch-Pagan	0.75	p-v = 0.29
Skewness	T= 0.83 ; p-v = 0.04	T = -0.48 ; p-v = 0.21
Kurtosis	T = 4.07 ; p-v = 0.08	T= 2.95 ; p-v = 0.94

Table 11: Residue test results for the French and German cases, without winter 2016-2017.

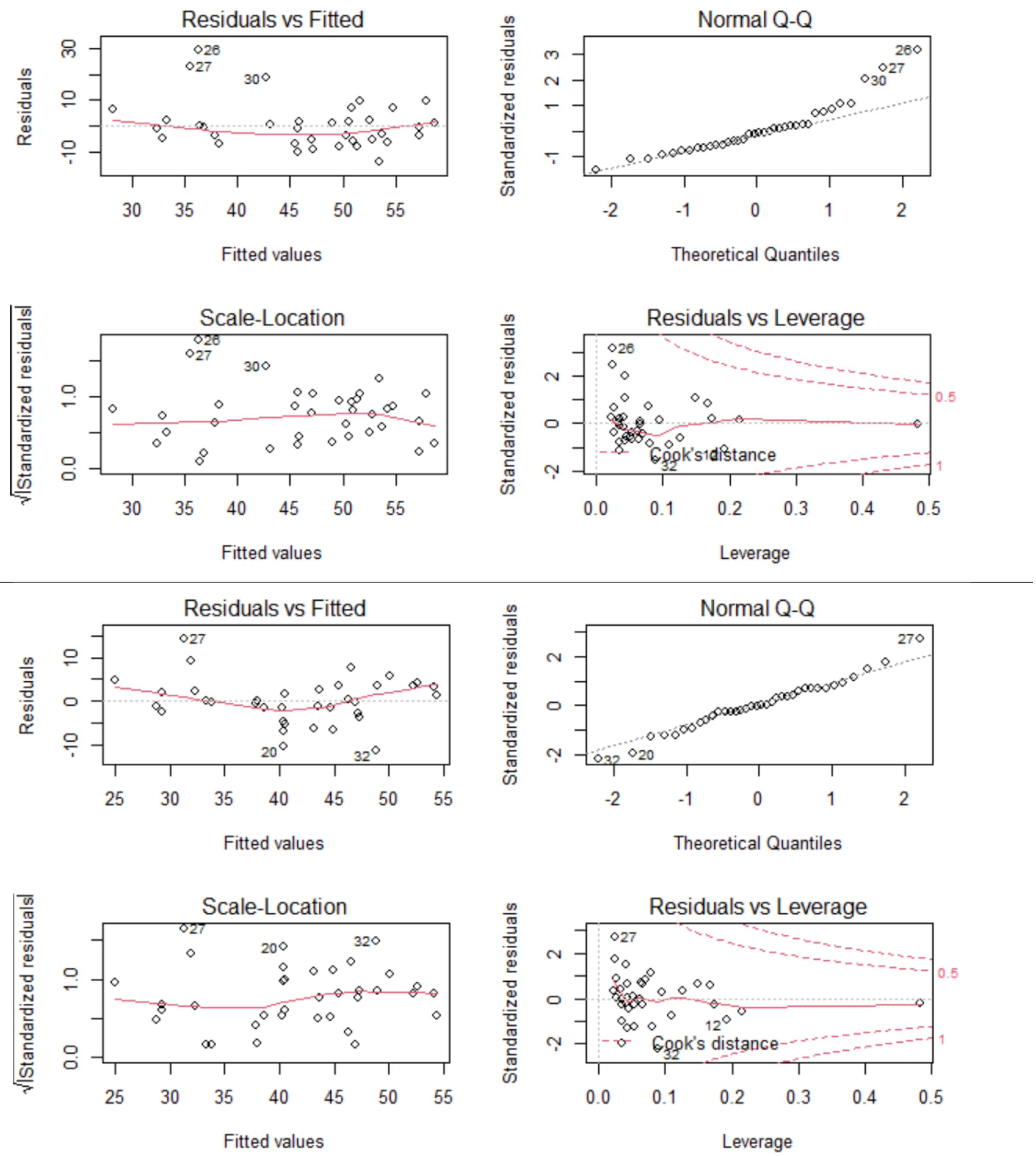


Figure 1: Model residuals (the first 4 figures for France and the last 4 for Germany) with the complete database.

B Determination of CCfD in Europe and limitations of the results

This annex presents the CCfD for the European case, assuming a single electricity price in the European Union.

B.1 Data

B.1.1 Estimation of the parameters

Given the absence of a single electricity price in Europe, we use the average price for this region, which is provided by the French transmission system operator [RTE, 2016]. This allows us to obtain an estimate of the electricity function parameters for the average of the European Union countries. Aware of the imperfection of this method, the analysis of the French case with RTE data is also presented in order to compare the results obtained with the two data sources (RTE [2016] and CRE [2010–2019]).

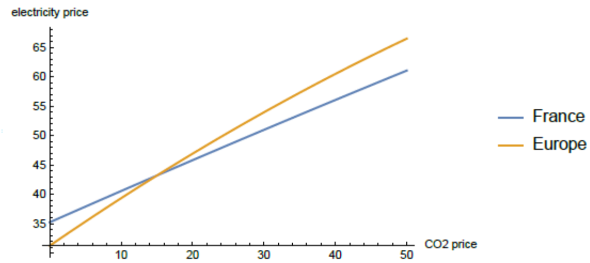
	France	Europe
p_0	35.266	31.286
p_1	0.5361	0.8343
p_2	-0.0004	-0.0026

Table 12: Reference values of electricity price parameters (€/MWh) in Europe and France, with $p_e(\sigma) = p_2\sigma^2 + p_1\sigma + p_0$.

Unlike the section 3.1.1, the parameter p_0 is non-zero while the parameter p_3 is. The influence of the power generation fleet (i.e. the impact of the price of the marginal technology called) is here integrated in the constant (p_0). While this distinction with the estimation based on CRE data implies different results summarized in the rest of this section, one can note the strong sensitivity of the CCfD characteristics to the electricity mix.

B.1.2 Production marginal costs analysis

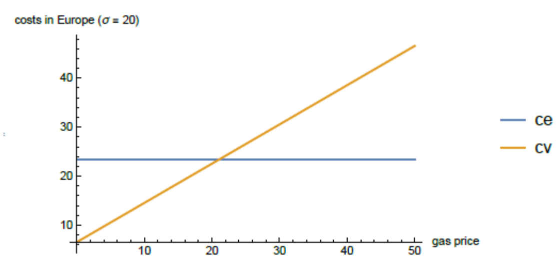
First, the variable costs of PtH production (i.e. electricity prices) are lower for a decarbonized fleet as in the French case than for the average of the European fleet (for a CO_2 price higher than 15 €/t) as can be seen in the Figure 2.



Interpretation: The above curves represent the price of electricity as a function of the price of carbon in France (blue curve: $p_0 = 35.266$; $p_1 = 0.5361$; $p_2 = -0.0004$) and in Europe (yellow curve: $p_0 = 31.286$; $p_1 = 0.8343$; $p_2 = -0.0026$). These prices are identical for a carbon price of 15€/t.

Figure 2: Electricity price (€/MWh) versus CO_2 price (€/t).

Also, gas prices have a strong influence on SMR production costs, and thus on the strike and payment of the CCfD. This impact is shown in Figure 5. The consequences of Proposition 1 are illustrated there: there is a threshold gas price such that CCfD is not useful since, whatever the carbon price, hydrogen by electrolysis is cheaper than by steam reforming. However, due to the different shape of the electricity price function and the value of its parameters, this threshold price ($\bar{p}_g^{\chi,a}$) is lower than in the French and German cases since, for Europe, $\bar{p}_g^{\chi,a} = 21.46$€/MWh while, in France, $\bar{p}_g^{\chi,a} = 47.19$€/MWh (with the CRE data) and, in Germany, $\bar{p}_g^{\chi,a} = 31.15$€/MWh

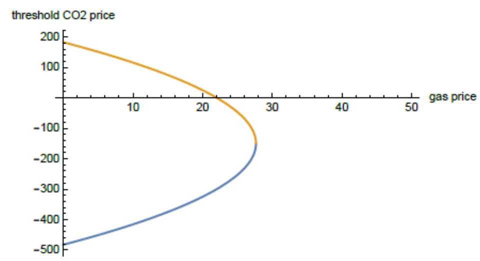


Interpretation: The blue (respectively orange) curve represents, as a function of the gas price (€/MWh), the marginal costs of hydrogen production by electrolysis (resp. steam reforming) in Europe (i.e. for parameters whose values are those of Tables 3 and 12, when the carbon price is 20€/t. For any gas price below 21.46 €/MWh, the marginal cost of PtH is higher than that of SMR.

Figure 3: Marginal costs of both technologies in Europe.

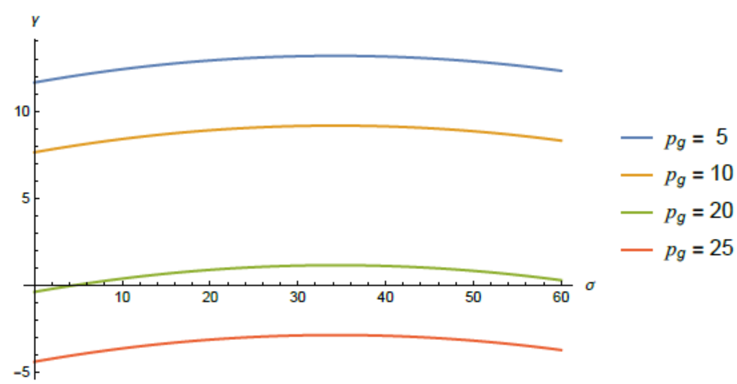
B.2 Analysis of the CCfDstrike and payement characteristics

B.2.1 Without additional support



Interpretation: The curve above represents the CCfD strike for the average European country. More precisely, the couple $(\sigma_m; \sigma_M)$ for this region. The abscissa of the connection point of the σ_m and σ_M curves corresponds to $\bar{p}_g^{\chi,a}$ defined in (2.10) i.e. the gas price above which the CCfD is useless. It is equal to 21.47€/MWh. For any pair (p_g, σ) inside this curve, the payment to the producer will be positive.

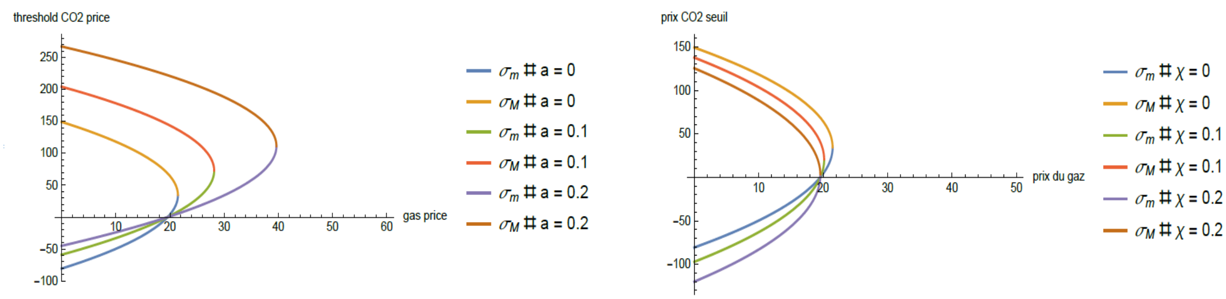
Figure 4: CCfD Strikes in Europe.



Interpretation: The curves above represent the CCfD payment in Europe as a function of the market carbon price (€/t) and different gas prices (€/MWh). Above a certain gas price (21.46€/MWh for the European case without additional support), the payment is negative whatever the carbon price, i.e. the CCfD is not useful. This is visible for $p_g = 25$.

Figure 5: Payment of CCfD in Europe according to the price of gas.

B.2.2 Impact of additional Sate Aids



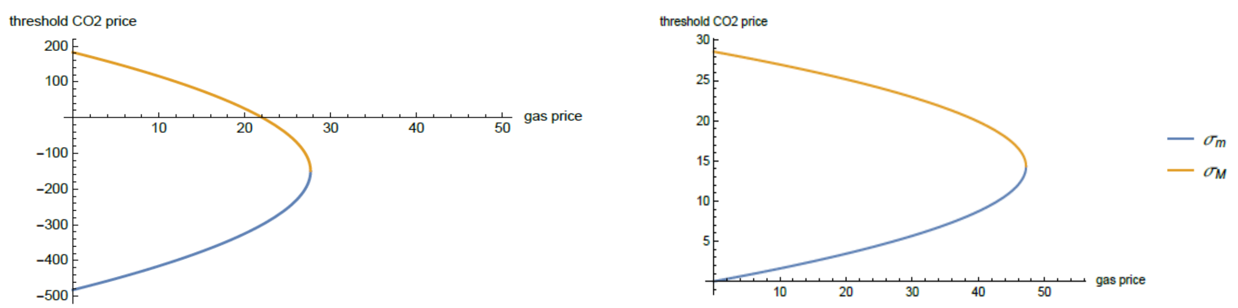
Impact of free allocations for SMR. Impact of carbon offsets for electrolysis.

Interpretation: The curves above represent the changes in the strike (in €/t) - function of the gas price (in €/MWh), following free allocations of emission permits for steam reforming (on the left) and compensation of indirect carbon effects for electrolysis (on the right).

Figure 6: Impacts of aid supplementing the carbon market on the CCFD strike in Europe.

B.3 Comparison of the results obtained with the two data sets with the French case

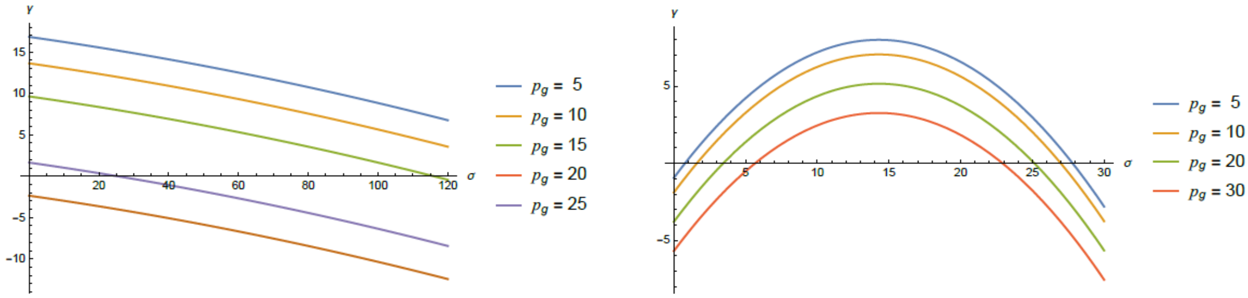
The comparison of the results obtained with the two data sources highlights the sensitivity of the strike and the payment to the two data sources (c.f. Figures 7 and 8) and suggests that errors could result from imperfections in the data collected and/or errors in the prediction of the reference parameters.



Threshold prices of CO_2 obtained with RTE data. Threshold prices of CO_2 obtained with CRE data.

Interpretation: These curves represent the different threshold prices (in €/t) - functions of the gas price (in €/MWh), obtained from RTE data (left) and CRE data (right).

Figure 7: Comparison of the French strikes obtained with CRE and RTE data.



Payments obtained with RTE data. Payments obtained with CRE data.

Interpretation : These curves represent the different payments (in €/MWh) obtained from RTE data (left) and CRE data (right), according to several gas prices (in €/MWh).

Figure 8: Comparison of the French payments obtained with CRE and RTE data.