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

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ABSTRACT

While the development of a low-carbon hydrogen economy in the European Union is currently a keystone of the energy transition, electrolysis production is not yet competitive with fossil fuel steam reforming. To remedy this, this study characterizes a new policy tool, the Carbon Contract for Difference (CCfD). This is a public policy instrument that guarantees a "low-carbon" producer a sufficiently high CO2 price to make its alternative technology less emissive but more expensive than existing technologies competitive. The authors propose a methodology for policymakers to design CCfDs according to their region and sectoral application. The study focuses on the design of a CCfD for the development of hydrogen by electrolysis as an alternative to steam reforming. It suggests that an economically efficient CCfD for hydrogen should be defined for areas with a homogeneous electricity mix. This CCfD should be designed according to the gas prices and state aid currently used in the EU-ETS system.

Keywords: Energy transition, Energy cost, Economic, CCfD, low-carbon hydrogen, emission reduction, EU-ETS

JEL: H23, O33, O38, Q56,D47, Q48, Q52

1. INTRODUCTION

Low-carbon hydrogen is now a crucial tool for the energy transition. This gas is commonly used for industrial purposes around the world. Hydrogen demand comes mainly from refineries and the chemical industry, accounting for more than 90% of consumption. The rest of the demand is divided between metallurgy, food processing, energy production and transportation. Its trade is currently flourishing with world consumption of “pure” hydrogen (not mixed with other gases) increasing from less than 20Mt/year in 1975 to more than 70Mt in 2018 according to IEA (2019). That same year 2018, European hydrogen production capacity reached 9.9Mt/year (Hydrogen Europe, 2020b). According to Hydrogen Futur, this growth has occurred in successive waves of interest closely linked to two factors: the rise in oil prices with the oil shocks and the growing consideration of climate issues. Indeed, the production of hydrogen is currently very polluting since it is almost exclusively based on the vaporization of fossil energy (SMR, for “Steam Methan Reforming”). Also the world production of hydrogen is responsible for 830Mt of carbon emissions, equivalent to the CO2 emissions of Indoesia and the United Kingdom combined (IEA, 2019). In Europe alone, 18% of greenhouse gas emissions is due to the production of basic industrial materials based on hydrogen, such as chemical inputs, cement or steel (Sartor and Bataille, 2019).

Thus, produced without emitting greenhouse gases, this dihydrogen (H2) commonly called decarbonized hydrogen, is a gas with many virtues. IEA (2019) highlights the many advantages of

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hydrogen, which explains the current enthusiasm of countries for its development. Indeed, about 50 countries in the world have implemented policies to support low-carbon hydrogen production. In the European Union, most of Member States see it as beneficial for the decarbonization of hard-to-abate sectors and for the flexibility of energy networks (FCH2JU, 2020). Decarbonizing this production by substituting clean technologies for polluting ones in hard-to-abate sectors 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.

In this study, our focus is concentrated on the European Union where low-carbon 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 concrete 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, 2020b).

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 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

[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.

[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 €80 per ton on December 6th, 2021, so Sartor and Bataille (2019) findings from 2019 should be viewed with caution.

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 advantages of this measure are highlighted by the literature.

To begin with, this contract is promoted for its risk reduction potential for low-carbon innovations investors. Actually, Jeddi et al. (2021) explain the contract makes it possible to reduce two types of risks borne by investors in low-carbon projects. The first one is the *damage risk* which is linked to changes in the carbon price over time due to changes in the perception of environmental damage. In this sense, Chiappinelli and Neuhoff (2020) demonstrate CCfDs can reduce 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 environmental damage valuation by the community and, thus, the market carbon price. A second risk borne by investor in low-carbon projects correspond to a *variable cost risk* caused by the immaturity[6] of the new technology compared to the cost competitiveness of the existing technology. Thus, by setting a higher carbon price, CCfD would allow innovation projects to overcome the "valley of death"[7], after the R&D phase. In this way and 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 due to a lower risk premium. Richstein and Neuhoff (2020) extend this reasoning by demonstrating the CCfD also reduces the necessary carbon price[8] for investment in the project. Indeed, by setting a fix carbon price, the CCfD secure the project's revenues and allows the competitiveness of the investment for a lower carbon price. In the same vein, Jeddi et al. (2021) show, with a general equilibrium model, that the CCfD allows to reach a higher collective surplus than in situations where the carbon price is fixed or totally flexible. For this dual hedging, the CCfD is considered by Gerres and Linares (2020) as the best coverage tool for decarbonized technologies to date.

Second, CCfDs have the advantage of being politically feasible. From an empirical point of view, this tool is already being considered or even implemented by a growing number of governments. For example, the EC suggests the use of CCfD in its hydrogen strategy and in the fit for 55 (European Commission, 2020, 2021). Germany is considering it in its hydrogen strategy (Federal Government, 2020) and the Netherlands has implemented it in its energy plan (Netherlands Enterprise Agency, 2020). This impetus can be explained by the following advantages. First, Chiappinelli and Neuhoff (2020) indicate the government 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 according to Sartor and Bataille (2019). Then, these authors 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. These advantages may expain why Chiappinelli et al. (2021) mention this tool as one of the policies that could be useful for decarbonization in a post-covid recovery context.

As the benefits of CCfD have already been studied, our study complements this literature in two respects. First, previous studies remain unclear on the precise design of the contract. While

[6]Most of low-carbon innovations are bearing higher marginal costs than existing technologies due to higher costs of inputs or maintenance.

[7]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.

[8]The "necessary carbon price" is understood as the carbon price sufficient for the competitiveness of low-carbon investments. In the absence of CCfD this price is setting (or not) by the market while, in the case of a CCfD, this price is setting by the strike.

authors put forward intuitive arguments to defend this or that characterization, a precise analysis to settle these debates has generally not been conducted in the existing literature.

There are usually six main characteristics of the contract. The first is the type of contract. Thus, some authors complete the first characterization of CCfD from Helm and Hepburn (2005). For example, Richstein (2017) invites to consider what he calls project-based CCfD in order to specifically link the payment of the contract to the volume of emission reductions associated with a project and thus avoid subsidizing portfolios of technologies that would generate windfall profits. McWilliams and Zachmann (2021), on the other hand, focuse on a so-called "commercialization contract" contract that allows the scale-up low-carbon technologies just after the R&D phase. Hence, he advocates a contract without a payback period in order not to disincentivize investors to contract.

Therefore, the type of contract has an influence on the second characteristic: the duration of the contract. While Helm and Hepburn (2005) consider a long-term contract, between 20 and 30 years, to allow for a phase that fully repays the subsidy period, McWilliams and Zachmann (2021) consider that a period of 3 to 5 years is sufficient to cover the marketing phase alone.

The third characteristic is the scale of the measure implementation. Most authors favour a European development of the contract, arguing that the more homogeneous the measure is between countries, the lower the cost of the policy will be, due to better competition between actors (Gerres and Linares, 2020). However, as the German and Dutch examples make clear, governments seem to opt for national development of CCfDs in the low-carbon hydrogen support case. Actually, this second option is in line with our results, as explained further below.

Finally, the last three characteristics - allocation methods, strike[9] and contract payment - are the least studied in the literature, although they are of great importance for public authorities. To our knowledge, the authors are unanimous in recommending a multi-stage auction system to select the beneficiaries of the contract and the associated strike price and payment (Helm and Hepburn, 2005; Richstein, 2017; Sartor and Bataille, 2019; Gerres and Linares, 2020). In this case, perfect competition between low-carbon investors would reveal the most efficient technology (unbiased technology selection) and the associated threshold price. However, public authorities seem to favor upstream technology selection and a threshold price ceiling. Indeed, perfect competition is difficult to achieve in practice. In addition, countries may have an interest in selecting the upstream sector of activity in order to meet their national emissions reduction targets. Whatever the allocation system considered, no study, to our knowledge, has studied in detail the construction of the strike and the payment associated with the contract. This information seems to be crucial for the public authorities and investors concerned. One may therefore wonder what the strike and payment associated with the CCfD would be at the end of a perfect allocation system (perfect expectations and information of the public authorities or perfect competition in an auction system).

The second contribution of our study is the analysis of CCfD in the specific case of hydrogen electrolysis development. While to our knowledge, it has not been studied yet, it seems this tool could be adapted to it. Indeed, Talebian et al. (2021) are interested in the effectiveness of existing or potential policies [10] 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[11], the authors show that the most effective policies to support large-scale production from central electrolysis are subsidies for operating costs (OPEX), ahead of investment subsidies and a ban on SMR production. In this context, CCfDs can be considered

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

[10]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).

[11]H2SCOT is a mixed integer linear model.

as a subsidy to OPEX since they reduce operating cost risks. Also, Richstein and Neuhoff (2020) emphasize the relevance of CCfDs in the case where there is 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 price than the SMR one (RTE, 2020b). 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. Thus, the implementation of a CCfD for the development of low-carbon hydrogen could complement the EU-ETS system whose current design seems insufficient to allow electrolysis to be competitive with steam reforming.

Thus, the objective of this study is to analyse the construction of "perfect" CCfD's strike and payment allowing to support PtH development. 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). We argue for the benefits of a reimbursement phase to avoid windfall profits. Finally, 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 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 EU-ETS market design. These marginal costs are a function of the prices of gas and carbon for SMR technology and of electricity prices (which are a function of carbon price and marginal cost of the last production unit called) for PtH technology. 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 Hydrogen, a self-consumed production

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 technology (SMR), represented by $j \in 1, \ldots, J)$ where K_j^s is the j producer's production capacity. The second is the group of hydrogen producers by electrolysis (PtH), represented by $i \in (i = 1, \ldots, I)$ where K_i^e is the production capacity of producer i.

SMR is the predominant technology and its production capacity is sufficient to meet the entire hydrogen demand, noted $D(p_h)$ where p_h is the hydrogen price. On the other hand, the capacity of PtH cannot meet all the demand. These assumptions reflect the current situation. Indeed, according to Hydrogen Europe (2020b), the European demand in 2018 is 8.3Mt of hydrogen while the electrolysis installed capacity is only 0.18 Mt. While the scenarios foresee an increase in this demand up to 56.3 Mt by 2050 (FCH2JU, 2019), the planned investments in electrolysis would only allow the production of 4.38 Mt in 2040. Thus, we can pose the following assumptions.

Assumption 2.1 *Capacities of firms using SMR (respectively PtH) technology are sufficient (resp.*

inadequate) to satisfy aggregate demand i.e. for all p_h

$$\sum_{j=1}^{J} K_j^s \geq D(p_h), \tag{1}$$

$$\sum_{i=1}^{I} K_i^e < D(p_h). \tag{2}$$

In 2020, two thirds of the European hydrogen production was consumed on-site. The rest of the production is divided between the market production and the by-product in the industrial processes (Hydrogen Europe, 2020b). Therefore, we assume that production and consumption are co-located[12].

2.1.2 Electrolysis, a currently not economically viable process

The SMR marginal cost is an increasing function of the gas price, the CO_2 emission factor and the CO_2 price on the EU-ETS and a decreasing function of the technology efficiency. The PtH marginal cost is a decreasing function of the electrolysis efficiency and an increasing function of the electricity price.

Given the observable marginal costs of both technologies (BEIS, 2021; European Commission, 2020)[13] and the scenarios of *The Fuel Cells and Hydrogen Joint Undertaking* (FCH2JU, 2020), the following hypothesis is realistic at the time of writing.

Assumption 2.2 *The SMR marginal cost is lower than the PtH one.*

Given the marginal cost structure, for electrolysis to be economically viable (i.e. the hypothesis 2.2 is no longer verified), it is necessary to have either better electrolysis efficiency (e.g. higher efficiency, lower maintenance), or electricity prices that are competitive with the price of gas used for steam reforming, or higher carbon prices for steam reforming. However, electricity, gas and carbon prices are mostly determined by markets and can therefore hardly be influenced. In addition, improving technological efficiencies takes time. Other solutions, such as CCfDs, can therefore be envisaged to make low-carbon hydrogen competitive.

2.2 The use of CCfDs for competitive low-carbon hydrogen

A potential solution for 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 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 (Sartor and Bataille, 2019).

CCfDs are long-term contracts[14] whose only variable is the carbon price. Consequently, whoever develops this type of contract for the hydrogen industry should make previsions (or scenarios) for gas and electricity prices as well as for the technologies' yield and the emission factor during the contract length and thus consider what we call in the following "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

[12] We discuss this assumption in 2.4.2.

[13] According to several studies (BEIS, 2021; Hydrogen Europe, 2020b; Hydrogen Council, 2021), The vast majority of marginal production costs for both technologies are explained by input prices. This explains the price difference between the two productions (European Commission, 2020)

[14] Sartor and Bataille (2019) suggest a duration of 5 to 10 years, Richstein and Neuhoff (2020) a duration of 3 to 20 years and Helm and Hepburn (2005) consider a duration of 20 to 30 years.

function of carbon prices[15], 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 of the combustibles, the efficiency of the technologies and their emission factors are known and constant over the duration of the CCfD.

2.3 Determination of the CCfD strike and payment

The determination of the CCfD strike and payment is based on the reference marginal costs of both technologies calculated from reference prices, yields and CO2 emission factors. In 2.3.1 these marginal cost functions are specified and then the strike and CCfD payment are determined in parts 2.3.2 and 2.3.3.

2.3.1 Marginal reference cost specifications

The marginal reference cost of hydrogen production by **SMR** (c_{sr}) is a function of the gas reference price (p_{gr}), the technology reference efficiency (ρ_{sr}), the CO_2 emission factor (e_s) and the CO_2 price on the EU-ETS (σ), which is

$$c_{sr}(\sigma, p_{gr}) = p_{gr}\rho_{sr} + e_s\sigma. \tag{3}$$

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 reference cost of production by steam reforming technology can be rewritten[16] as

$$c^a_{sr}(\sigma, p_{gr}) = p_{gr}\rho_{sr} + (e_s - a)\sigma. \tag{4}$$

The marginal reference cost of hydrogen production by **electrolysis technology** (c_{er}) is a function of its reference efficiency (ρ_{er}) and the electricity price (p_{er}). However, as previously mentioned, the latter depends on the market carbon (σ) and fuel prices. Thus, we set

$$c_{er}(\sigma, p_{gr}) = p_{er}(\sigma, p_{gr})\rho_{er}, \tag{5}$$
$$p_{er}(\sigma, p_{gr}) = p_0 + p_1\sigma + p_2\sigma^2 + p_3 p_{gr}, \tag{6}$$

where $p_0 \geq 0$, $p_1 > 0$, $p_2 < 0$ et $p_3 \geq 0$. 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[17] 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 (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

[15]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.

[16]In this analysis, we consider all the unitary taxes or subsidises as part of marginal costs.

[17]This adaptation is true even in the short term because of the fuel switch.

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 $c_{er}(\sigma) - c_{er}(0)$, can be offset by unitary subsidies[18] noted $\chi \in [0; 1]$. Taking into account these subsidies, the marginal reference cost of electrolysis production is rewritten as

$$c^{\chi}_{er}(\sigma, p_{gr}) = c_{er}(\sigma, p_{gr}) - \chi(c_{er}(\sigma, p_{gr}) - c_{er}(0, p_{gr})). \tag{7}$$

Remark 2.3 *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*[18].

2.3.2 The CCfD strike

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 reference production costs of the two technologies are equal. Thus, if we note $\gamma^{\chi,a}(\sigma, p_{gr})$ the difference between the two production marginal reference costs i.e.

$$\gamma^{\chi,a}(\sigma, p_{gr}) = c^{\chi}_{er}(\sigma, p_{gr}) - c^{a}_{sr}(\sigma, p_{gr}), \tag{8}$$

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

$$\gamma^{\chi,a}(\sigma, p_{gr}) = 0. \tag{9}$$

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 assumptions, $\gamma^{\chi,a}$ in a concave function of the CO_2 price[19]. It is decreasing (respectively increasing) in the gas price if ρ_{er} is lower (resp. higher) than $\frac{\rho_{gr}}{p_3}$[20]. It is decreasing with the efficiency of the SMR technology and increasing with the efficiency of the PtH technology.

The equation 9 solutions number depends, among other things, on the value of the gas reference price. Thus, we can state the Proposition 2.4.

Proposition 2.4 *Let's denote $\bar{p}^{\chi,a}_{g}$ the gas price that cancels the discriminant of the polynomial 9, i.e.*

$$\bar{p}^{\chi,a}_{gr} = -\frac{(e_s - a)^2 - 2p_1(e_s - a)\rho_{er}(1-\chi) + \rho^2_{er}(p^2_1(1-\chi) - 4p_0p_2)(1-\chi)}{4p_2\rho_{er}(\rho_{gr} - p_3\rho_{er})(1-\chi)}. \tag{10}$$

As a result,

1. *If $p_{gr} > \bar{p}^{\chi,a}_{gr}$ then for all σ, $\gamma^{\chi,a}(\sigma, p_{gr}) < 0$ i.e. whatever the carbon price, the SMR technology is more expensive than the PtH technology. In this case, there is no need to set up a CCfD.*

[18]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.

[19]Indeed, from (4)–(5), we have $\frac{\partial \gamma^{\chi,a}(\sigma,p_{gr})}{\partial \sigma} = \rho_{er}(p_1 + 2p_2\sigma)(1-\chi) - (e_v - a)$ and $\frac{\partial^2 \gamma^{\chi,a}(\sigma,p_{gr})}{\partial \sigma^2} = 2p_2\rho_{er}(1-\chi) < 0$.

[20]Indeed, $\frac{\partial \gamma^{\chi,a}(\sigma,p_{gr})}{\partial p_{gr}} = p_3\rho_{er} - \rho_{gr}$.

2. *If $p_{gr} = \bar{p}^{\chi,a}_{gr}$, then the equation 9 has a solution, noted $\bar{\sigma}^{\chi,a}$. Whatever the carbon price, SMR technology is more expensive than PtH technology*[21]*. As a result, the CCfD is inefficient in this case.*

3. *If $p_{gr} < \bar{p}^{\chi,a}_{gr}$ then there are two carbon price thresholds, $\bar{\sigma}^{\chi,a}_m$ and $\bar{\sigma}^{\chi,a}_M$, 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 $\bar{\sigma}^{\chi,a}$, $\bar{\sigma}^{\chi,a}_m$ and $\bar{\sigma}^{\chi,a}_M$ are

$$\bar{\sigma}^{\chi,a} = \frac{(e_s - a)}{2p_2\rho_{er}(1-\chi)} - \frac{p_1}{2p_2}, \tag{11}$$

$$\bar{\sigma}^{\chi,a}_m = \bar{\sigma}^{\chi,a} - \frac{\Gamma_1}{\Gamma_2}, \tag{12}$$

$$\bar{\sigma}^{\chi,a}_M = \bar{\sigma}^{\chi,a} + \frac{\Gamma_1}{\Gamma_2}, \tag{13}$$

where

$$\Gamma_1 = \sqrt{(e_s - a - p_1\rho_{er}(1-\chi))^2 + (4p_2\rho_{er}(-p_0\rho_{er} + p_{gr}(\rho_{gr} - p_3\rho_{er})))(1-\chi)}, \tag{14}$$

$$\Gamma_2 = -2p_2\rho_{er}(1-\chi). \tag{15}$$

Property 2.5 *By assumption $p_2 < 0$, therefore if $p_g < \bar{p}^{\chi,a}_g$ and if $\sigma \in]\bar{\sigma}^{\chi,a}_m; \bar{\sigma}^{\chi,a}_M[$ then $c_{er} > c_{sr}$ or else $c_{er} \le c_{sr}$.*

Properties 2.6 *The solutions of the equation 9 verify:*

1. $\bar{\sigma}^{\chi,a}_m \le \bar{\sigma}^{\chi,a}_M$ *and* $\frac{\partial \bar{\sigma}^{\chi,a}_m}{\partial p_{gr}} = -\frac{\partial \bar{\sigma}^{\chi,a}_M}{\partial p_{gr}}$.
2. *If the impact of the reference gas price on the marginal cost of PtH is lower (resp. higher) than the reference SMR yield , i.e. $\rho_{er} \times p_3 < \rho_{gr}$, then $\sigma^{\chi,a}_m$ is increasing (resp. decreasing) and $\sigma^{\chi,a}_M$ is decreasing (resp. increasing) in p_{gr}.*
3. *If the carbon price has a higher impact on the marginal cost of SMR than on the marginal cost of PtH, i.e. $(e_s - a) \ge (p_1\rho_{er}(1-\chi))$, then at least one of the solutions of 9 is negative. Indeed, in this case, $\bar{\sigma}^{\chi,a} \le 0$ and $\bar{\sigma}^{\chi,a}_m < 0$, regardless of the reference gas price.*
   (a) *If in addition, the reference gas price is higher than $p^M_{gr} = \frac{p_0\rho_{er}}{\rho_{gr} - p_3\rho_{er}}$ then $\bar{\sigma}^{\chi,a}_M < 0$ and, as a result, the CCfD is useless.*
   (b) *If the reference gas price is lower than p^M_{gr} then $\bar{\sigma}^{\chi,a}_M \ge 0$.*
4. *If $(e_s - a) \le p_1\rho_{er}(1-\chi)$ then $\bar{\sigma}^{\chi,a} \ge 0$ and $\sigma^{\chi,a}_M > 0$, regardless of the reference gas price.*
   (a) *If in addition, the reference gas price is higher than p^M_{gr} then $\bar{\sigma}^{\chi,a}_m > 0$*
   (b) *Si $p_{gr} < p^M_{gr}$ then $\bar{\sigma}^{\chi,a}_m < 0$*

Given Properties 2.5–2.6 and Proposition 2.4, the following theorem, which defines the strike, can be stated.

Theorem 2.7 *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 ($\bar{p}^{\chi,a}_g$) and*

- *if $(e_s - a) \le p_1\rho_{er}(1-\chi)$ and if $p_{gr} > p^M_{gr}$* ***the couple*** $(\bar{\sigma}^{\chi,a}_m, \bar{\sigma}^{\chi,a}_M)$ ***constitutes the strike,***

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

- *if* $(e_s - a) \leq p_1\rho_{er}(1-\chi)$ *and if* $p_{gr} \leq p_{gr}^M$ ***the strike is*** $\bar{\sigma}_M^{\chi,a}$,
- *if* $(e_s - a) > p_1\rho_{er}(1-\chi)$ *and if* $p_{gr} \leq p_{gr}^M$ ***the strike is*** $\bar{\sigma}_M^{\chi,a}$.

In other cases, the CCfD is useless[22].

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 possible existence of two thresholds, i.e. a couple of carbon prices which constitute the strike.

2.3.3 The payment formula

The CCfD payment formula, function of the selected strike, is defined in the Theorem 2.8.

Theorem 2.8 *If the reference gas price* p_{gr} *is less than* $\bar{p}_g^{\chi,a}$ *and if* $p_{gr} > p_{gr}^M$ *when* $(e_s - a) \leq p_1\rho_{er}(1-\chi)$*, then in order to guarantee the competitiveness (in expectation) of PtH compared to that SMR, 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_t) *and of the selected strike. More precisely, at t*

$$\bar{\gamma}^{\chi,a}(\sigma_t) = \Gamma_1(\bar{\sigma}_M - \sigma_t) - \frac{\Gamma_2}{2}(\bar{\sigma}_M - \sigma_t)^2 \tag{16}$$

where Γ_1 *is defined by (14) and* Γ_2 *by (15).*

Property 2.9 *If the strike is the couple* $(\bar{\sigma}_m^{\chi,a}, \bar{\sigma}_M^{\chi,a})$ *then the payment* $\bar{\gamma}^{\chi,a}(\sigma_t)$ *can also be written as*

$$\bar{\gamma}^{\chi,a}(\sigma_t) = -\Gamma_1(\bar{\sigma}_m - \sigma_t) - \frac{\Gamma_2}{2}(\bar{\sigma}_m - \sigma_t)^2. \tag{17}$$

Property 2.10 *From the second point of 2.6 properties, the more the equation of electricity price (6) parameter* p_3 *is high (resp. low), the more* $\bar{\gamma}^{\chi,a}(\sigma_t)$ *is important (resp. small), all other thing being equal.*

The payment $\bar{\gamma}^{\chi,a}(\sigma_t)$ can either be a unitary production subsidy or a unitary tax on production. Indeed, $\bar{\gamma}^{\chi,a}(\sigma_t) \in \mathbb{R}^+$ is negative if the carbon price is lower than $\bar{\sigma}_m$ or higher than $\bar{\sigma}_M$. In other words, the payment is a unitary tax akin to a reimbursement when PtH hydrogen is more competitive than SMR one during the periode t. To cope with this situation, two political options can be considered:

1. Either the State cancells the negative payments;
2. Or the State demands this reimbursement.

We discuss both possibilities is the next section which is devoted to the study of the temporal effects of CCfDs.

2.4 The CCfD, a long-term contract

2.4.1 The CCfD, a renegotiable contract

The negative payment (i.e. $\bar{\gamma}^{\chi,a}(\sigma_t) < 0$) is akin to a form of reimbursement from the contracted producers to the government. Nonetheless, the payback at time t does not imply a higher

[22] The equation 9 solutions, if any, are negatives.

cost of the PtH technology compared to SMR one if the baseline values are equal to the actual values at time t. Consequently, if the objective of the CCfD is to compensate for the lack of competitiveness of PtH hydrogen compared to SMR hydrogen and not to make the SMR uncompetitive, the reimbursement must be considered. Then, $\bar{\gamma}^{\chi,a}(\sigma_t)$ may be negative. Therefore, under the hypothesis that during the period t (e.g. annual) the quantity produced by the producer benefiting from the contract ($\bar{i}$) $q_{\bar{i}}(t) \leq K^e_{\bar{i}}$ is constant[23], the payment of $\bar{i}$ is $\bar{\gamma}^{\chi,a}(\sigma_t) \times q_{\bar{i}}(t)$.

However, in the duration of the CCfD, it is very likely that the reference values/scenarios do not correspond to the actual values at time t. In this case, we may have

$$c^{\chi}_e(\sigma_t, p_{g,t}) - \bar{\gamma}^{\chi,a}(\sigma_t) \neq c^a_s(\sigma_t, p_{g,t}), \tag{18}$$

where $p_{g,t}$ is the gas price at t, $c^{\chi}_e(\sigma_t, p_{g,t})$ and $c^a_s(\sigma_t, p_{g,t})$ are marginal costs of both technologies at t and $\bar{\gamma}^{\chi,a}(\sigma_t)$ is the payment, which is, for its part, according to the baseline values. Therefore in this situation, the surplus of the producer benefiting from CCfD may differ from what he would have obtained with the SMR technology. These surplus differences are

$$\Delta S_{\bar{i}}(t) = (c^a_s(\sigma_t, p_{g,t}) - c^{\chi}_e(\sigma_, p_{g,t}) + \bar{\gamma}^{\chi,a}(\sigma_t))q_{\bar{i}}(t). \tag{19}$$

If the baseline values of the CCfD are verified then for all PtH hydrogen producers benefiting of the contract, the sum over t of the surpluses is zero, i.e $\forall \bar{i}$, $\sum_{t=1}^{T} \Delta S_{\bar{i}}(t) = 0$. This confirms that even if the payment is negative, the producer would still have to pay the amount $\bar{\gamma}^{\chi,a}(\sigma_t) \times q_{\bar{i}}(t)$ to the public authorities.

However, gas and/or electricity price shocks [24] at $t = t_c$ can contribute to the sum $\sum_{t=1}^{t_c-1} \Delta S_{\bar{i}}(t) + \mathbb{E}_{t_c} \sum_{t=t_c}^{T} \Delta S_{\bar{i}}(t)$ diverging from zero. In this case, renegotiation of the contract should be considered. The same should apply if, at $t = t_r$, the amount $|\sum_{t=1}^{t_r} \Delta S_{\bar{i}}(t)|$ is too high.

2.4.2 New entrants in the hydrogen market

During the multiple years of the contract, the CCfD could have another use than the substitution of SMR by PtH for a self-consumed production of low-carbon hydrogen. It may also contribute to the development of commercialized decarbonized hydrogen (Hydrogen Europe, 2020a; Hydrogen Council, 2021). We do not determine the equilibrium on this growing market, because given the importance of transport costs (BEIS, 2021), a horizontal differentiation model should be considered. However, we can draw some conclusions by logical reasoning. Today, the price of commercialized hydrogen is driven by the cost of steam reforming. CCfDs should contribute to the replacement of SMR production capacities by PtH ones. More precisely, the number of producers using electrolysis technology noted $I(t)$ should increase with time $\left(\frac{dI(t)}{dt} > 0\right)$ and that using $J(t)$ technology should decrease $\left(\frac{dJ(t)}{dt} > 0\right)$. Consequently, there is a moment $\bar{T}$ from which, for any $t \geq \bar{T}$, there exists a price of hydrogen (p_h) such as $\sum_{j}^{J(t)} K_j < D(p_h)$. In this case, the hypothesis 2.1 is no longer verified and, above all, the SMR technology will not be the only technology that will guide the price. The interest of this CCfD will then be reduced or even null as soon as the sum of the payments $\bar{\gamma}^{\chi,a}(\sigma_t)$ over the duration of the contract is null.

It is also very likely that if CCfDs are made at different times t, with new entrants to the market, their characteristics (strike and payment) will differ, due to different baseline values/scenarios. As a result, the terms of the equations in the previous sections should be differentiated according to the date of contract signing. We have not done so in order not to complicate the notation. Because

[23] This assumption is relaxed in 5.1.

[24] The latter are characterized in the model by changes in the value of the parameters of the price equation 6 due to changes in available production capacity, demand shocks and fuel prices.

of the construction of the CCfD (payment formula and possibility of renegotiation) a producer who signs on a different date than another should not be at an advantage or disadvantage compared to his competitor.

2.4.3 Interactions with other polities

This section examines the possible interactions, over the CCfD duration, between the contract and two other public policies, namely the EU-ETS carbon market and the Contracts for Difference (CfD) for electricity prices.

Regarding interactions with the carbon market, a string of literature has focused on the so-called overlap between additional policies and the carbon market. Thus, in their study, Perino et al. (2020) define an overlap as a decarbonization policy carried by a single Member State and/or concerning a sub-sector of the EU-ETS. This definition fits well the CCfD tool, which targets a sub-sector covered by the EU-ETS (i.e. industries) and can be implemented on a national scale. In the context of this overlapping, the authors characterize the perverse effect called the *waterbed* effect. Perino et al. (2020) define it as the compensation of the reduction of emissions in a sector (caused by an additional policy to the EU-ETS) by the increase of emissions in other sectors due to the carbon price decrease. Also, in a pure cap-and-trade system, with a fixed cap and a perfect market, this effect leads to a total substitution of emissions from one sector to another. In the CCfD case, this would mean that the decrease in emissions from the substitution of MSR for PtH would be fully offset by the increase in emissions in other sectors of the EU-ETS due to the fall in permit prices. However, with the new Market Stability Reserve (MSR) rule (Chaton et al., 2018; Bruninx et al., 2020; Azarova and Mier, 2021), the EU-ETS system is a hybrid system with a flexible permit cap in the short and long term. Indeed, the MSR is a tool that complements the EU-ETS since 2019 and allows the carbon market to adapt to exogenous shocks and variations in the demand for permits. It is a reserve in which surplus permits are stored after being withdrawn from the market. With a threshold mechanism, permits are re-injected into the market if supply is deemed insufficient. Beginning in 2023, the MSR may permanently remove a certain volume of allowances if the permits placed in reserve exceed the volume auctioned the previous year (European Parliament and Council, 2018). According to Perino et al. (2020), the MSR would mitigate the waterbed effect. Indeed, if we assume that the MSR can take permits in all periods, then the waterbed effect is perforated as the authors put it. This means that the decrease in emissions in one sector is not fully compensated since the MSR stores the additional permits. According to their analysis, the magnitude of the perverse effect of the waterbed is smaller. Thus, one can think that the waterbed effect in the case of CCfD could be compensated by the MSR but this phenomenon may deserve a more specific study.

The second policy considered in this part is the Contract for Difference for decarbonized electricity. This contract appears at first glance to be close to the CCfD. It guarantees contractors a fixed price for electricity, thus covering the volatility of the market price for low-carbon energy providers (Alao and Cuffe, 2021). However, as Gerres and Linares (2020) note, the CfD covers the entire business plan of the electrician, unlike the CCfD, which only covers the carbon price. This tool, which is used to support the development of low-carbon electricity, can interact with the CCfD in two cases. Either the CfD is implemented prior to the CCfD, or it is implemented after the CCfD but still during its lifetime. In the first case, the construction of the CCfD takes into account the influence of the CfD on electricity prices. However, in the second case, the reference values for electricity prices do not take into account the introduction of a CfD on them. Therefore, a renegotiation of the CCfD can be considered.

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. We chose to focus the study on these two countries for two reasons. The first is their stated interest in the development of hydrogen. Indeed, both countries have established ambitious strategies for the development of low-carbon hydrogen (cf. Ministry of Ecological Transition, 2020; Federal Government, 2020). Secondly, these countries are representative of the heterogeneity of the electricity production fleets within the EU. In France, more than 90% of electricity is decarbonized. It is mainly produced from nuclear power (around 70%) and hydro power (13%), with a small share of fossil fuels (7.5%) (RTE, 2020a). In contrast, the German electricity mix includes a large share of fossil fuels (51% divided between coal, natural gas and oil), with a small share of nuclear power (11%). That being so, while in France, emissions related to electricity and heat production represent only 12.4% of 2019 national emissions, in Germany they represent 42.3% of 2017 national emissions according to IEA (2021, 2020).

To begin our analysis, the data set used is first detailed. Estimates of the electricity price function parameters (equation 6) are presented. Then, an analysis of the costs of hydrogen produced by both 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 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_{er}). The observations for the carbon prices are front-year prices[25] from ICE Endex[26].

The ordinary least squares estimate results are available in appendix 5.2. We summarize here the final results. We retain the following specification of the electricity function

$$p_{er} = p_1\sigma + p_2\sigma^2 + p_3 p_{gr} + \epsilon, \tag{20}$$

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 (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

[25] 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.

[26] C.f ICE Endex.

Table 1: Linear regression results for the French case.

Explanatory var.	**Parameter**	Estimation	SD	t-value	$P(>\|t\|)$
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

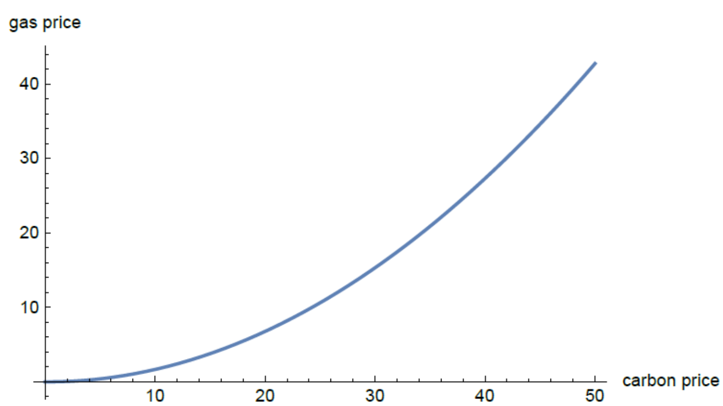
Table 2: Linear regression results for the German case.

Explanatory var.	**Parameter**	Estimation	SD	t-value	$P(>\|t\|)$
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

being equal, is more important in France (equal to 1.22) than in Germany (equal to 1). Consequently, given the property 2.10 the payment of the French CCfD is more important than the German one. We can see this in the following (cf. Figure 8).

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).

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



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.

Note that if we consider only positive electricity prices, the specification 20 is only valid for certain values of the carbon price i.e. $\sigma \in [\max\left(0, \frac{p_1-\sqrt{p_1^2-4p_2p_3p_g}}{-2p_2}\right); \frac{p_1+\sqrt{p_1^2-4p_2p_3p_g}}{-2p_2}]$.

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).

We did not consider a reference gas price, because given the possible existence of tensions on the gas markets[27] it seemed more appropriate to conduct a sensitivity analysis of the marginal

[27] Tensions can be observed, for example, in the third quarter of 2021 and at the beginning of 2022 (Internation gas prices, 2021).

Table 3: Reference values of the model parameters.

ρ_{gr}	e_s	ρ_{er}	a	χ
80%	$0.328gCO_2/MWh$	50%	0	0

costs, the strike and the CCfD payment to the gas price.

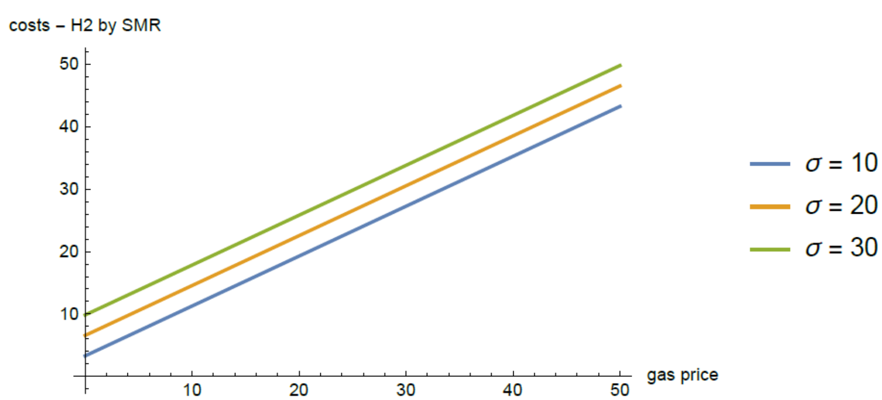
Given the parameters values, we have $p_1\rho_{er}(1-\chi) = 1.58(1-\chi)$ for the French and German cases. As $e_s = 0.328$, for any χ less than $0.792405 + 0.632911a$, we have $(e_s - a) \leq p_1\rho_{er}(1-\chi)$. However, due to the European legislation[28], χ is always smaller 0,75. In addition, as $p_0 = 0$ for both countries, we have $p^M_{gr} = \frac{p_0\rho_{er}}{\rho_{gr}-p_3\rho_{er}} = 0$. As a result, the strike is constituted by the couple $(\bar{\sigma}^{\chi,a}_m, \bar{\sigma}^{\chi,a}_M)$.To simplify the writing, we will note hereafter the thresholds as σ_m and σ_M.

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 both technologies, since it is the difference between these two marginal production costs that needs to be compensated with the contract.

Independently of the studied region, SMR production marginal cost (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.

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



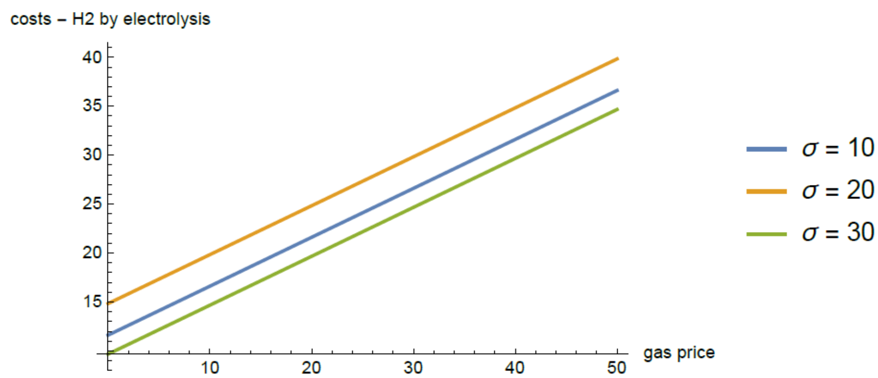
Interpretation: The lines above represent the marginal costs of hydrogen production by SMR as a function of the gas price, for certain values of the carbon price, σ, when the efficiency of the technology ρ_g is 80%, the carbon emission factor e_s is 32.8% and without free allocation of carbon emission 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).

The case of electrolytic generation is slightly more sophisticated. If the parameter p_3 of the electricity price function (6) is non-zero[29] (case for France and Germany) then the PtH marginal cost (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

[28] cf. footnote 18.
[29] If $p_3 = 0$ then the marginal cost of hydrogen production by electrolysis is independent of the gas price.

any $\sigma > -p_1/2p_2$. This is why, on Figure 3, the line for $\sigma = 10$€/t is between the lines $\sigma = 20$€/t and $\sigma = 30$€/t.

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

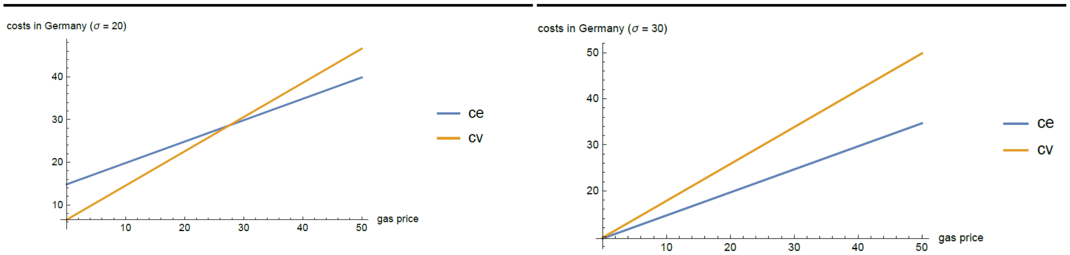


Interpretation: The lines above represent the PtH marginal costs in Germany as a function of the gas price when the technology efficiency ρ_e is 50% and without carbon offsetting ($\chi = 0$). These lines are increasing (resp. decreasing) if the price of carbon σ is less (resp. more) than 19.75€/t.

Given the value of the selected parameters (Table 3), we assume that the SMR marginal costs (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.

Figure 4: Costs of both technologies in Germany.

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

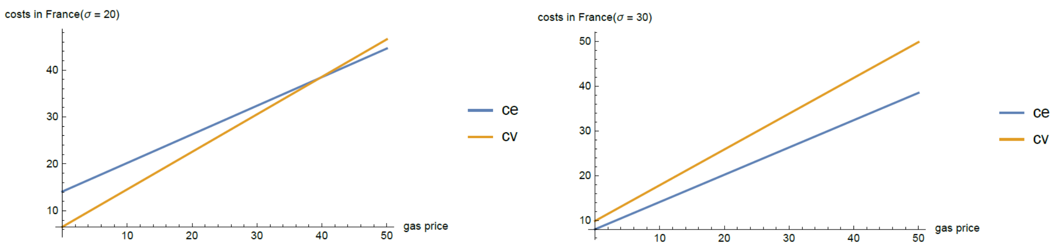


Interpretation: The blue (respectively orange) curves represent, as a function of the gas price (€/MWh), the marginal costs of hydrogen production by electrolysis (resp. steam reforming) in Germany (i.e. for parameters whose values are those of Tables 2 and 3, when the carbon price is 20€/t (left figure)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

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

Figure 5: Costs of both technologies in France.

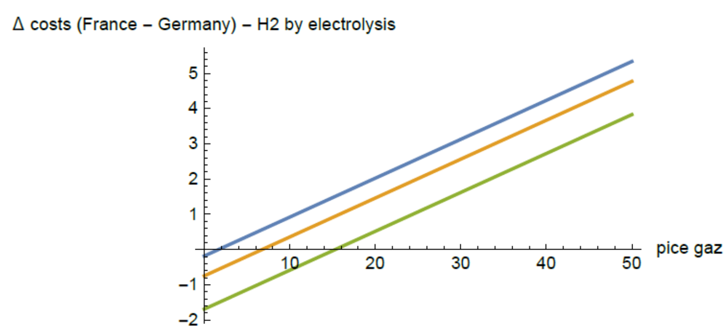
Costs for a carbon price of 20€/t. | **Costs for a carbon price of 30€/t.**



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.

than French production (for a gas price higher than or equal to 1.7€/MWh), for $\sigma = 30$€/t, the trend can be reversed according to the gas price (see Figure 6). There is a threshold gas price (function of σ)[30] 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.

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



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.

3.4 Analysis of the CCfD's price and payment

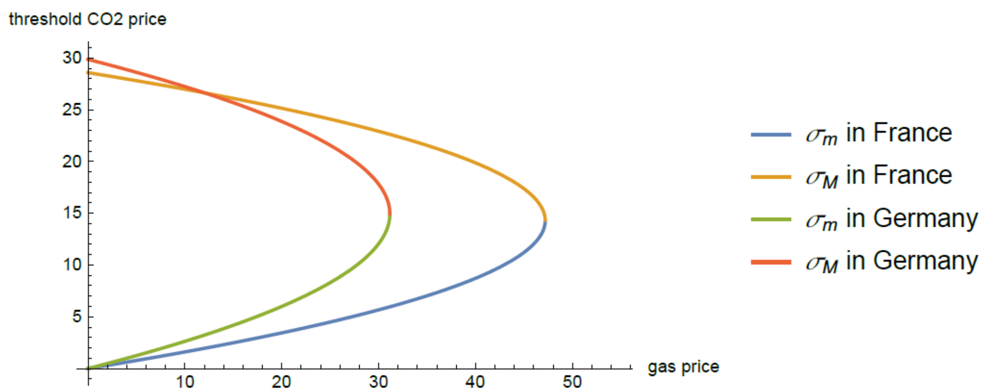
3.4.1 CCfD characteristics without additional State aid

As noted earlier, the existence of distinct electricity prices across generation assets leads to regionally specific CCfDs, as illustrated in Figure 13. In this figure, electrolysis production is more

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

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*[31]. From Proposition 2.4, 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.

Figure 7: CCfD strikes in France and Germany.



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 (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.

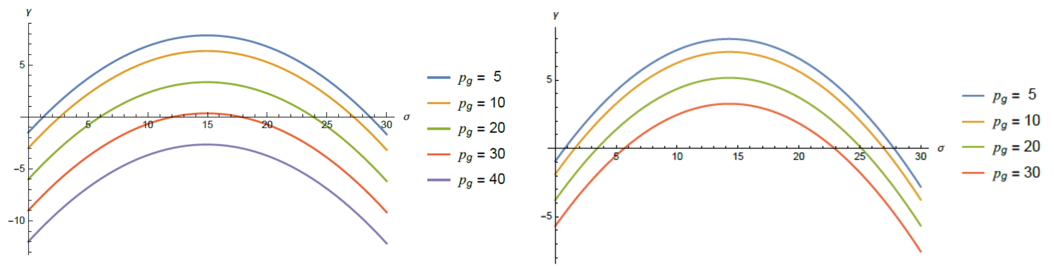
Therefore, for an equal CO_2 price on the market, the payments made by the government to producers can be higher in France than in Germany, as illustrated in Figure 8. For example, for a gas price of 30€/MWh, the payment is slightly positive in Germany for a market carbon price between 12 and 17€/t, 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 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 (10) and calculated previously (see Figure 13 for example).

Example. Suppose that the CCfD developer estimates that, over the contract period, the gas price will be 20€/MWh. Given the electricity price specification (20), 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.).

[31] Given the values of the parameters we have chosen, the strikes (French and German) are made up of couples. More precisely, and without additional State aid, 1. for the French case $\sigma_m(p_g) \approx 12.52 - 10\sqrt{1.5675 - 0.038p_g}$ and $\sigma_m(p_g) \approx 12.52 + 10\sqrt{1.5675 - 0.038p_g}$; 2. for the German case $\sigma_m(p_g) \approx 15.65 - 12.5\sqrt{1.5675 - 0.048p_g}$ and $\sigma_M(p_g) \approx 15.65 + 12.5\sqrt{1.5675 - 0.048p_g}$.

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

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.

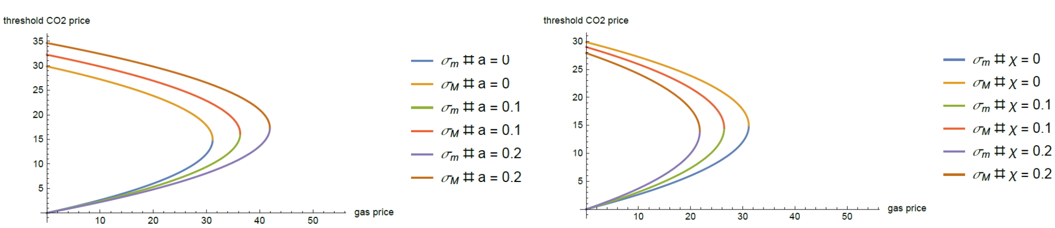
3.5 Impacts of state aid supplementing the EU-ETS

As a reminder, the developed model allows the study of two state aids complementing the EU-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.

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

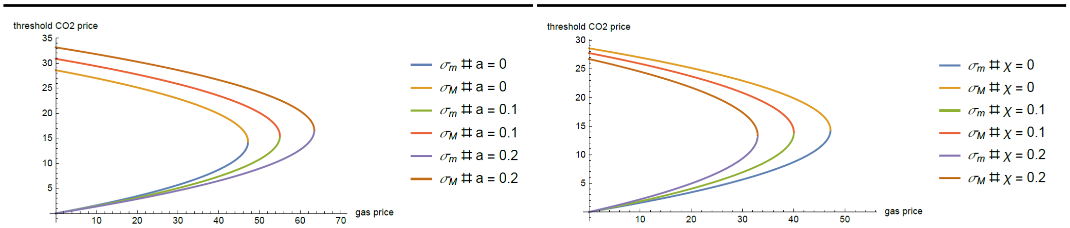
Impact of free allowances for SMR. | **Impact of carbon offsetting for electrolysis.**



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

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



4. CONCLUSION

This study focused on characterizing an efficient CCfD for the scale of low-carbon hydrogen by electrolysis production. Our analysis focuses on the marginal cost differential between SMR and PtH technologies. We focus only on hydrogen produced at the site of its consumption, primarily for industrial use.

By construction of the strike, 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 national electricity fleets. This conclusion could be reconsidered in two situations. First, in the hypothesis of the existence of a single electricity price in Europe, as studied in the annex, the CCfD could be established at a European level. Second, if the share of commercial hydrogen increases, a horizontal differentiation model should be study to analyse the effectiveness of a national implementation compared to a European one.

Then, 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.

Finally, we argue for a CCfD including a reimbursement phase in order to avoid windfall profits. Indeed, because of the construction of the CCfD's strike and payment, the reimbursement phase do not does not imply any loss for the contractor who produces by electrolysis compared to a situation where he produces by SMR.

The study of CCfD characteristics could be completed in the following three ways.First, 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. Then, 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. The overlap question should be dealt with in this study. Finally, a precise analyse of the allocation methods could be done.

5. APPENDIX

5.1 Hydrogen production varies throughout the year

Hydrogen production is not necessarily constant between two payment/repayment periods. As it is the same for CO_2 prices, if the duration between payments/repayments can be shortened the reasoning made in the main text holds. If not, it is sufficient to take these variations into account. For this purpose, in this appendix a period of duration d (e.g. 365 days) is no longer represented by t but by $(\tau = 1, \ldots, T)$. The time in the period is characterized by t. The State will not make the payment at each t but at the end of each τ period (annual if $d = 365$). Thus, if we note t_0 the date of the beginning of the CCfD, at the end of each τ period, the amount received by the low-carbon H producer who signed the CCfD ($\bar{i}$) and who produces the quantity $q_{\bar{i}} \leq K^e_{\bar{i}}$, is

$$P_{\bar{i}}(\tau) = \sum_{t=t_0+d(1-\tau)}^{t=t_0+d\times\tau} \bar{\gamma}^{\chi,a}(\sigma_t) \times q_{\bar{i}}(t) \tag{21}$$

where $\bar{\gamma}^{\chi,a}(\sigma_t)$ is defined by 16. Given that $\bar{\gamma}^{\chi,a}(\sigma_t) \in \mathbb{R}$, it is possible that $P_{\bar{i}}(\tau)$ is negative. Three policies are then possible:

- Either the State does not demand reimbursement, in this $P_{\bar{i}}(\tau)$ is rewritten

$$\max\left(\sum_{t=t_0+d(1-\tau)}^{t=t_0+d\times\tau} \bar{\gamma}^{\chi,a}(\sigma_t) \times q_{\bar{i}}(t), 0\right);$$

- Or the State cancells the negative payments $\bar{\gamma}^{\chi,a}(\sigma_t)$, in this case $P_{\bar{i}}(\tau)$ is rewritten

$$\sum_{t=t_0+d(1-\tau)}^{t=t_0+d\times\tau} \max(\bar{\gamma}^{\chi,a}(\sigma_t), 0) q_{\bar{i}}(t);$$

- Or again the State demands this reimbursement.

Consequently, if the objective of the CCfD is to compensate for the lack of competitiveness of PtH hydrogen compared to SMR hydrogen and not to make the SMR uncompetitive, the reimbursement must be considered. As a consequence, the State should neither cancell the payments $\bar{\gamma}^{\chi,a}(\sigma_t)$ nor the amounts $P_{\bar{i}}(\tau)$. Of course, the third option ($P_{\bar{i}}(\tau) \in \mathbb{R}$) is less expansive for the state than the first one ($P_{\bar{i}}(\tau) \in \mathbb{R}^+$), which is less expansive than the second one ($\bar{\gamma}^{\chi,a}(\sigma_t) \in \mathbb{R}^+$).

Obviously, it is rare that the reference values correspond to the values observed in t. In each period τ, the difference between the producer's surplus $\bar{i}$ and that which would have been obtained with the SMR technology is

$$\Delta S_{\bar{i}}(\tau) = \sum_{t=t_0+d(\tau-1)}^{t_0+d\times\tau} (c^a_s(\sigma_t, p_{g,t}) - c^\chi_e(\sigma, p_{g,t}) + \bar{\gamma}^{\chi,a}(\sigma_t)) q_{\bar{i}}(t). \tag{22}$$

If at $\tau = \tau_c$, $\sum_{\tau=1}^{\tau_c-1} \Delta S_{\bar{i}}(\tau) + \mathbb{E}_{\tau_c} \sum_{\tau=\tau_c}^{T} \Delta S_{\bar{i}}(\tau) \neq 0$, then the renegotiation should be considered. The same applies if at $\tau = \tau_r$, $|\Delta S_{\bar{i}}(\tau)|$ is high.

5.2 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 (6) for France and Germany are given in tables 4 and 5.

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

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 5: Results of the linear regression for the German 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

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.

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

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 7: Results of the linear regression for the German 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

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[32].

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 check for skewness and kurtosis: the results of the Kurtosis test invite us to check for the presence of outliers. We notice

[32] p-v = p-value.

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

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

on the residuals plot 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 (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.

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	1.22	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 10: Linear regression results for the German 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

5.3 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.

5.3.1 Data

5.3.2 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

Table 11: Residue test results for the French and German cases, 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

also presented in order to compare the results obtained with the two data sources (RTE (2016) and CRE (2010–2019)).

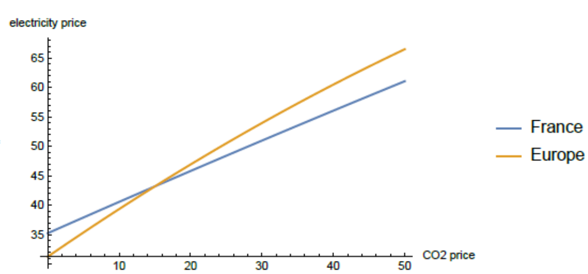
Table 12: Reference values of electricity price parameters (€/MWh) in Europe and France, with $p_e(\sigma) = p_2\sigma^2 + p_1\sigma + p_0$.

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

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.

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 11.

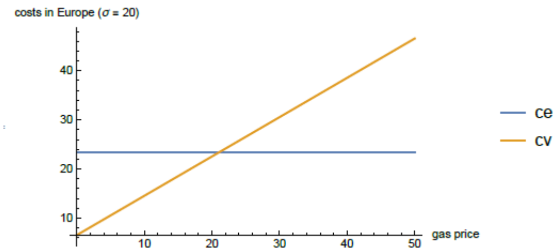
Figure 11: Electricity price (€/MWh) versus CO_2 price (€/t).



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.

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 14. 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.

Figure 12: Marginal costs of both technologies in Europe.

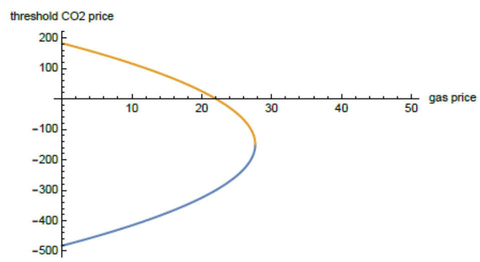


Interpretation: The blue (respectively orange) curve represents, as a function of the gas price (€/MWh), the marginal costs of hydrogen production by electrolysis (resp. steam reforming) in Europe (i.e. for parameters whose values are those of Tables 3 and 12, when the carbon price is 20€/t. For any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

5.3.3 Analysis of the CCfDstrike and payement characteristics

Without additional support

Figure 13: CCfD Strikes in Europe.



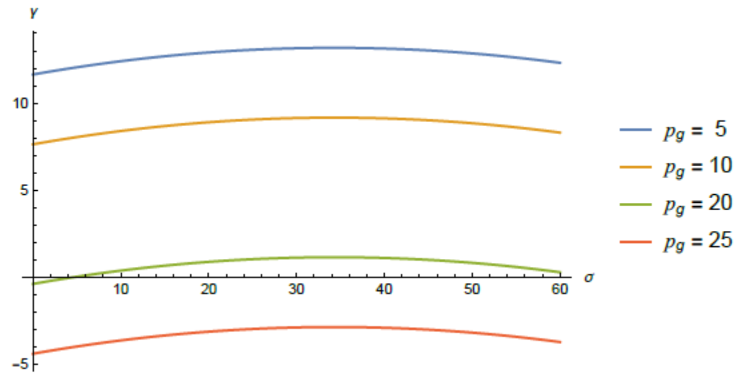
Interpretation: The curve above represents the CCfD strike for the average European country. More precisely, the couple $(\sigma_m; \sigma_M)$ for this region. The abscissa of the connection point of the σ_m and σ_M curves corresponds to $\bar{p}_g^{\chi,a}$ defined in (10) i.e. the gas price above which 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.

Impact of additional Sate Aids

5.3.4 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 16 and 17) and suggests that errors could result from imperfections in the data collected and/or errors in the prediction of the reference parameters.

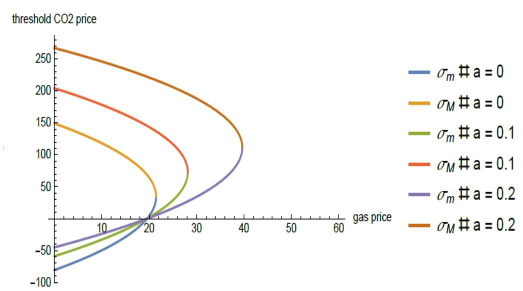
Figure 14: Payment of CCfD in Europe according to the price of gas.

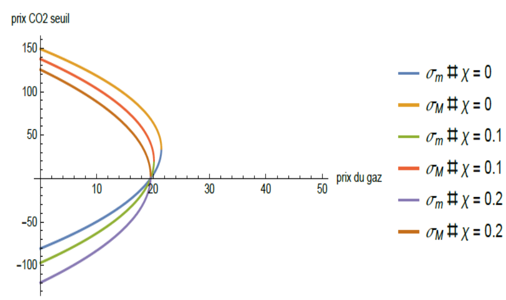


Interpretation: The curves above represent the CCfD payment in Europe as a function of the market carbon price (€/t) and different gas prices (€/MWh). Above a certain gas price (21.46€/MWh for the European case without additional support), the payment is negative whatever the carbon price, i.e. the CCfD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

Figure 15: Impacts of aid supplementing the carbon market on the CCFD strike in Europe.

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

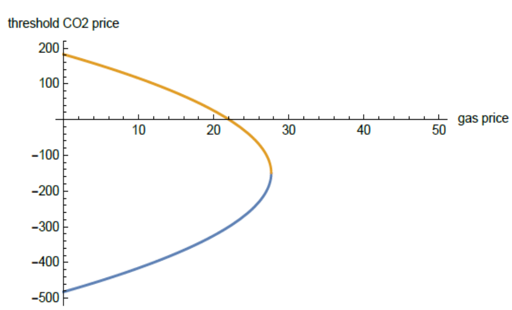


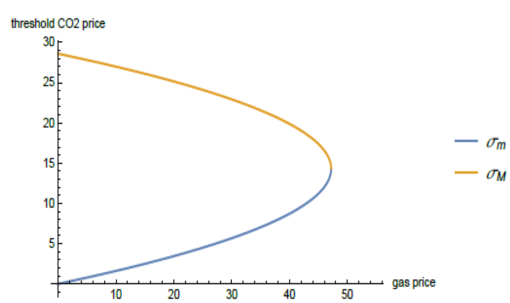


Interpretation: The curves above represent the changes in the strike (in €/t) - function of the gas price (in €/MWh), following free allocations of emission permits for steam reforming (on the left) and compensation of indirect carbon effects for electrolysis (on the right).

Figure 16: Comparison of the French strikes obtained with CRE and RTE data.

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

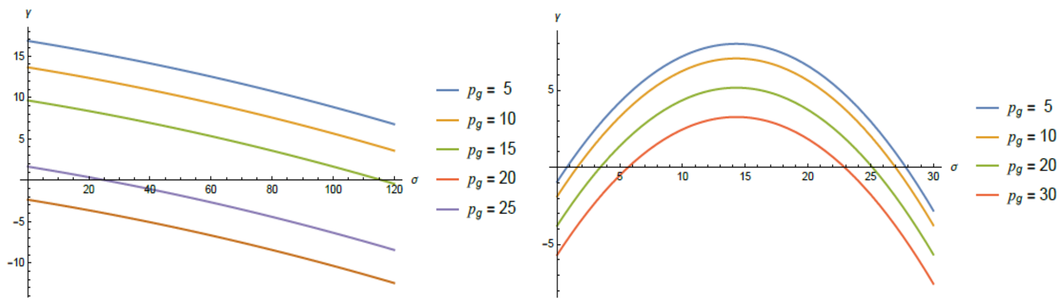




Interpretation: These curves represent the different threshold prices (in €/t) - functions of the gas price (in €/MWh), obtained from RTE data (left) and CRE data (right).

Figure 17: Comparison of the French payments 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).

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