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

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Context

Low-carbon hydrogen, an energy vector for decarbonization

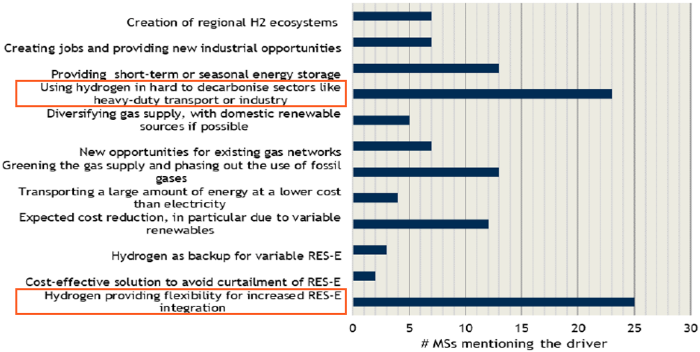

FIGURE – The main benefits expected by Member States from the development of low-carbon hydrogen, FCH2JU (2020)

Context

A product in need of competitiveness in the face of steam reforming production

Steam Reforming (SMR) = €1,5/kg
Power-to-Hydrogen (PtH) = €2,5-6/kg
Hydrogen Strategy, European Commission (2020)

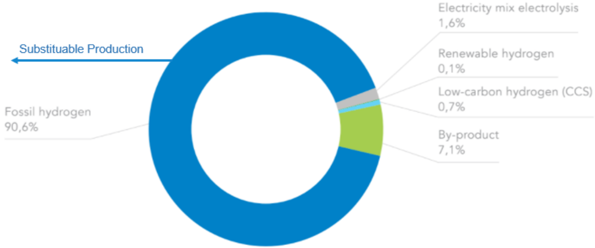

FIGURE – Distribution of H_2 production by technology in Europe in 2018, Hydrogen Europe (2020)

Context

The need for an effective carbon price to make up for the competitiveness gap

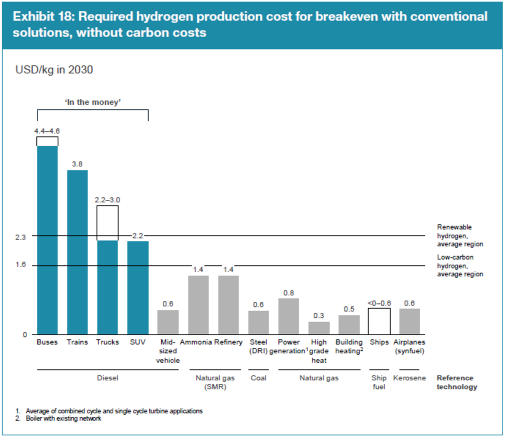

FIGURE – Low-carbon H_2 costs needed to achieve competitiveness without carbon price, Hydrogen Insights (2021)

Literature

The CCfD, a tool first described by Helm and Hepburn, 2005

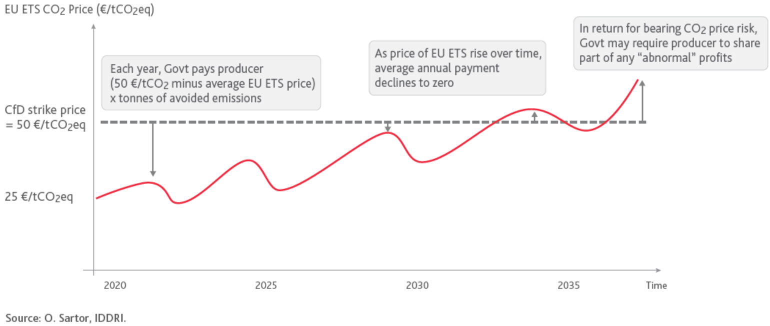

FIGURE – Example of how CCfD works to support the development of low-carbon investments

Literature

CCfD to support the scaling up of innovative low-carbon project

- Time consistency (Chiappinelli & Neuhoff, 2020)
- Lowering the required CO_2 price (Richstein & Neuhoff, 2020)
- Closing the funding gap (Richstein 2017)
- Consistency with political framework (Sartor & Bataille, 2020)

research question

How to design the CCfD to scale up low-carbon hydrogen production ?

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1- General framework : Price competition

Let n firms produce a homogeneous good H_2

The firm i profit

$$\Pi_i(p_{h_i}, p_{h_{-i}}) = (p_{h_i} - c_i) D_i(p_{h_i}, p_{h_{-i}}), \tag{1}$$

where $c_i = c_e$ (resp. $c_i = c_s$) the marginal cost of electrolysis (resp. of Steam reforming).

Nash equilibrium

As long as $c_s < c_e$, $p_h^\star = c_s$ and electrolysis H_2 is not cost-effective.

2- marginal costs specification

Let $i = \{e, v\}$, p_i be the price of energy used by technology i, *rho*$_i$ be the yield of i and *sigma* be the market price of CO_2..

Marginal cost of H_2 by steam reforming

$$c_s(\sigma, p_g) = p_g \rho_s + e_s \sigma. \quad (2)$$

Marginal cost of H_2 by electrolysis

$$c_e(\sigma, p_g) = p_e(\sigma, p_g)\rho_e, \quad (3)$$

where $p_0 \geq 0$, $p_1 > 0$, $p_2 < 0$ et $p_3 \geq 0$:

$$p_e(\sigma, p_g) = p_0 + p_1\sigma + p_2\sigma^2 + p_3 p_g. \quad (4)$$

2- marginal costs specification

With State Aids

Indirect carbon cost offset

A subsidy χ is possible for H_2 up to 75% of the indirect cost of CO_2. With $\chi[0,1]$, c_e can be rewritten as :

$$c_e^{\chi}(\sigma) = c_e(\sigma) - \chi(c_e(\sigma) - c_e(0)). \quad (5)$$

Free allocations of emission permits

If we consider the free allocations as unit subsidies reducing the marginal cost of CO_2 emissions for producers by steam reforming, denoted $a \in [0; e_s]$, then c_s is rewritten

$$c_s^a(\sigma, p_g) = p_g \rho_s + (e_s - a)\sigma. \quad (6)$$

3- CCfD strike and payment determination

Strike price and threshold gas price

Definition of the contract strike

The strike is defined by the solution(s) in *sigma* (with *sigma* $\in \mathbb{R}$) of the quadratic equation of the marginal costs difference :

$$\gamma^{\chi,a}(\sigma) = c_e^{\chi}(\sigma) - c_s^{a}(\sigma). \tag{7}$$

Definition of the threshold gas price

The gas price that cancels the discriminant of the polynomial $\bar{p}_g^{\chi,a} =$

$$-\frac{(e_s - a)^2 - 2p_1(e_s - a)\rho_e(1-\chi)}{4p_2\rho_e(\rho_g - p_3\rho_e)(1-\chi)} + \frac{\rho_e^2(p_1^2(1-\chi) - 4p_0p_2)}{4p_2\rho_e(\rho_g - p_3\rho_e)}. \tag{8}$$

3- CCfD strike and payment determination

CCfD efficiency condition

Proposition

1. If $p_g > \bar{p}_g^{\chi,a}$ then for all σ, $\gamma^{\chi,a}(\sigma, p_g) < 0$ i.e. there is no need to set up a CCfD.
2. If $p_g = \bar{p}_g^{\chi,a}$, then the equation 7 has a unique solution, noted $\bar{\sigma}^{\chi,a}$. As a result, the CCfD is inefficient in this case.
3. If $p_g < \bar{p}_g^{\chi,a}$ then $\exists!(\bar{\sigma}_m^{\chi,a}, \bar{\sigma}_M^{\chi,a})$ tq $\forall \sigma \in [\bar{\sigma}_m^{\chi,a}, \bar{\sigma}_M^{\chi,a}]$, $c_e > c_v$. Therefore, a CCfD could make low-carbon hydrogen competitive.

Theorem

The CCfD will be implemented only if the expected gas price is below the threshold $\bar{p}_g^{\chi,a}$ and the couple $(\bar{\sigma}_m^{\chi,a}, \bar{\sigma}_M^{\chi,a})$ is the strike.

3- CCfD strike and payment determination

The strike analytical expression

The analytical expression of the couple $(\bar{\sigma}_m^{\chi,a}, \bar{\sigma}_M^{\chi,a})$ is :

$$\bar{\sigma}_m^{\chi,a} = \bar{\sigma}^{\chi,a} - \frac{\Gamma_1}{\Gamma_2}, \tag{9}$$

$$\bar{\sigma}_M^{\chi,a} = \bar{\sigma}^{\chi,a} + \frac{\Gamma_1}{\Gamma_2}, \tag{10}$$

where $\Gamma_1 =$

$$\sqrt{(e_s - a - p_1\rho_e(1-\chi))^2 + (4p_2\rho_e(-p_0\rho_e + p_g(\rho_g - p_3\rho_e)))(1-\chi)} \tag{11}$$

$$\Gamma_2 = -2p_2\rho_e(1-\chi). \tag{12}$$

3- CCfD strike and payment determination

CCfD payment γ

The CCfD payment formula

$\gamma^{\chi}(\sigma)$ is the difference between the marginal costs i.e.

$$\gamma^{\chi,a}(\sigma) = c_e^{\chi}(\sigma) - c_s^{a}(\sigma). \tag{13}$$

Theorem

If the reference gas price is less than $\bar{p}_g^{\chi,a}$, then the contract payment noted $\bar{\gamma}^{\chi,a}$, is

$$\Gamma_1(\bar{\sigma}_M - \sigma) - \frac{\Gamma_2}{2}(\bar{\sigma}_M - \sigma)^2 = -\Gamma_1(\bar{\sigma}_m - \sigma) - \frac{\Gamma_2}{2}(\bar{\sigma}_m - \sigma)^2 \tag{14}$$

where Γ_1 and Γ_2 are defined by (11) and (12).

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1- Data : Electricity prices

$$p_e = p_1\sigma + p_2\sigma^2 + p_3 p_g + \epsilon, \qquad (15)$$

Explanatory var. $P(>\|t\|)$	Param.	Estimation	SD	t-value
p_g	p_3	1,22	0,18	2e-7
σ	p_1	3,16	0,78	0,000321
σ^2	p_2	-0,10	0,03	0,008178
p_g	p_3	1,00	0,12	2,7e-9
σ	p_1	3,16	0,52	8,76e-7
σ^2	p_2	-0,08	0,02	0,000285

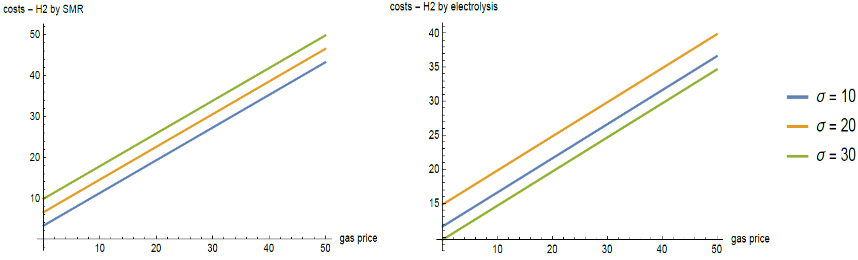
TABLE – Linear regression results for the French (top) and German (bottom) cases. Data : CRE, Observatoire des Marchés, 2010-2019

1- Data : other parameters

ρ_g	e_v	ρ_e	a	χ
80%	0,328gCO_2/MWh	50%	0	0

TABLE – Reference values of the model parameters.

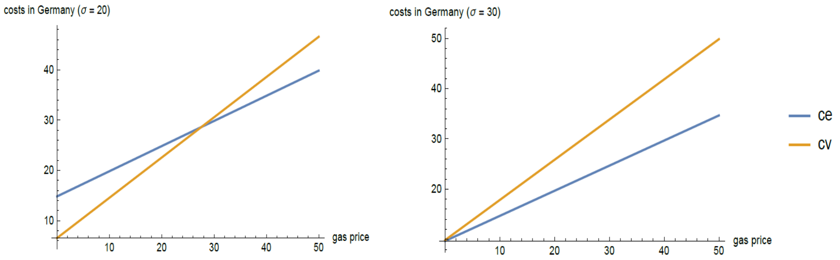
2- Analysis of hydrogen production costs



Steam reforming marginal costs Electrolysis marginal costs

FIGURE – Marginal costs of hydrogen (€/MWh) by both technologies as a function of the gas (€/MWh) and carbon (€/t) prices.

2- Analysis of hydrogen production costs



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

FIGURE – Costs of both technologies in Germany (€/MWh).
(blue = electrolysis, yellow = steam reforming)

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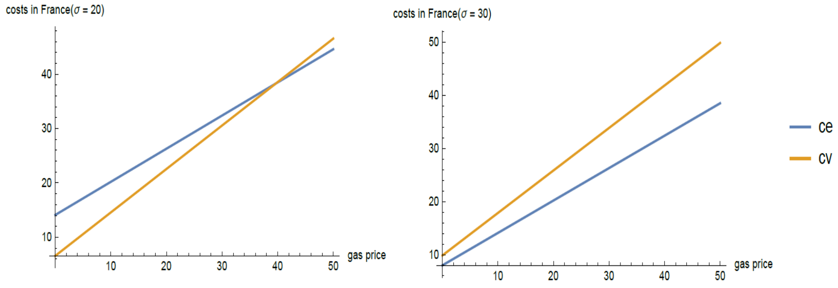


Costs for a carbon price of 20€/t. Costs for a carbon price of 30€/t.

FIGURE – Costs of both technologies in France (€/MWh).
(blue = electrolysis, yellow = steam reforming)

2- Analysis of hydrogen production costs

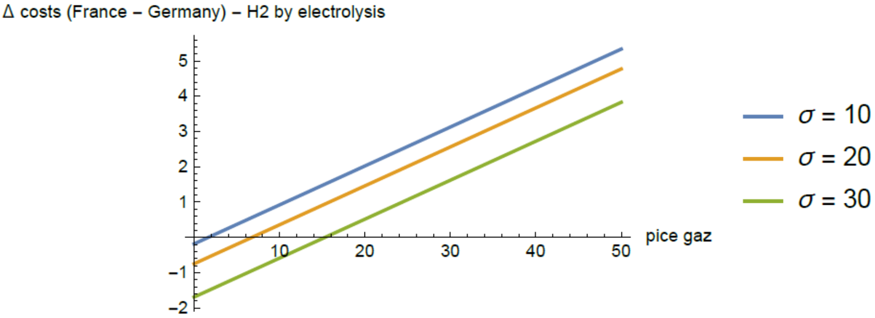


FIGURE – Difference in marginal costs of hydrogen production by electrolysis between France and Germany (€/MWh).

3- Analysis of the CCfDs price and payment characteristics

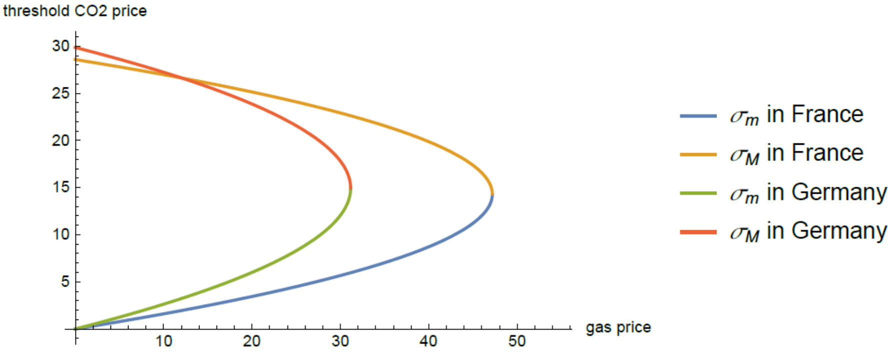
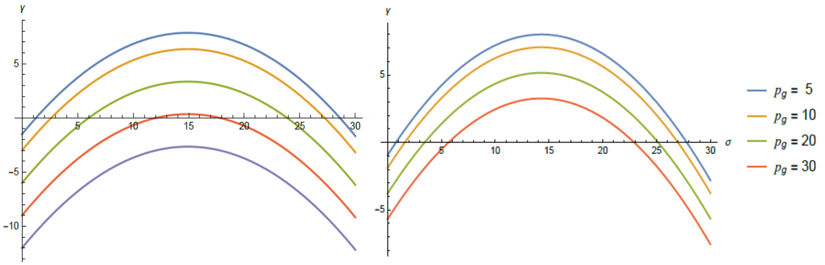


FIGURE – CCfD strikes (€/t) in France and Germany as a function of gaz price (€/MWh).

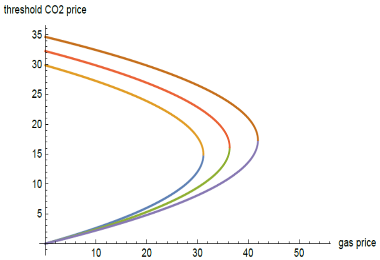
3- Analysis of the CCfDs price and payment characteristics



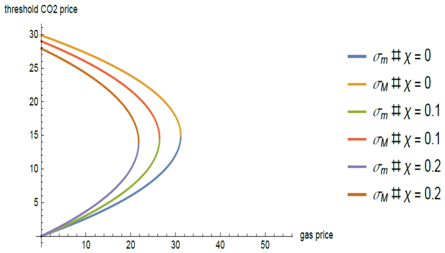
Germany France

FIGURE – CCfD payment (€/MWh) in France and Germany according to the carbon market price (€/t).

3- Analysis of the CCfDs price and payment characteristics



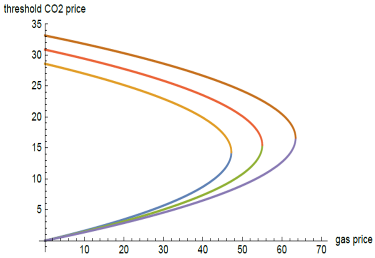
Impact of free allowances for steam reforming.



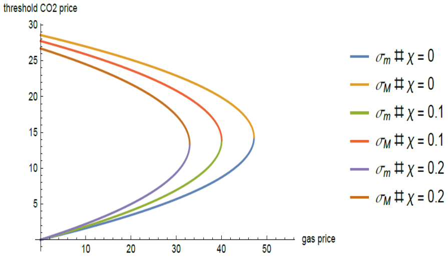
Impact of carbon offsetting for electrolysis.

FIGURE – Impacts of the subsidies supplementing the carbon market on the CCfD strike in Germany (€/t).

3- Analysis of the CCfDs price and payment characteristics



Impact of free allowances for steam reforming



Impact of carbon offsetting for electrolysis.

FIGURE – Impacts of the subsidies supplementing the carbon market on the CCfD strike in France (€/t).

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Conclusion

Results : An initial model on CCFDs and H_2

- The strike can represent a set of prices ;
- There is a threshold gas price (relative to other parameters) above which the CCfD is ineffective ;
- The CCfD should be characterized according to the region's electricity fleet due to the impact of the carbon price ;
- The additional aid to the EU-ETS impacts the characterization of CCfDs.

Further research

Multi-period model to consider the whole business plan (investments, uncertainty, risk coverage) ; study of allocation methods...

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Appendices

- A. Econometric study for the electricity price function in France and Germany
- B. Determination of CCfD in Europe and limitations of the results

A.1- Selection of variables *(French case)*

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
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 – Results of the linear regression for the French case with constant (top) and without constant (bottom).

A.2- Residue test

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 – Results of the residue tests for the French and German cases, with the complete database.

A.2- Residue test *(French case)*

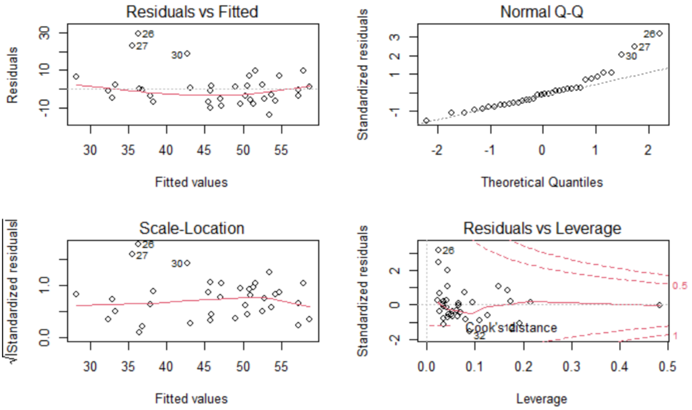

FIGURE – Model residuals for the French case with the complete database.

A.2- Residue test

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

B.1- Estimation of the parameters

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

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

B.2- Strike and payment for the European case

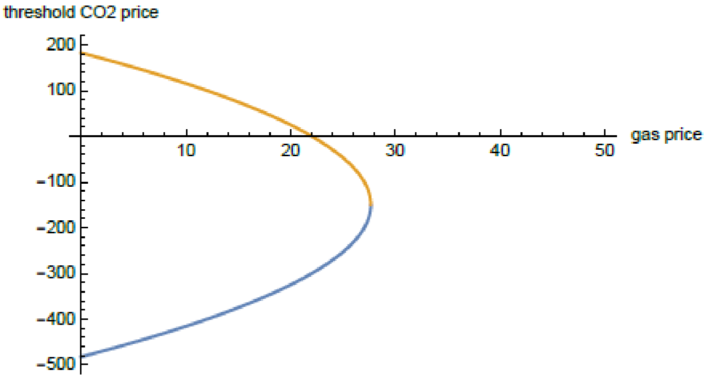

FIGURE – CCfD strike in Europe.

B.2- Strike and payment for the European case

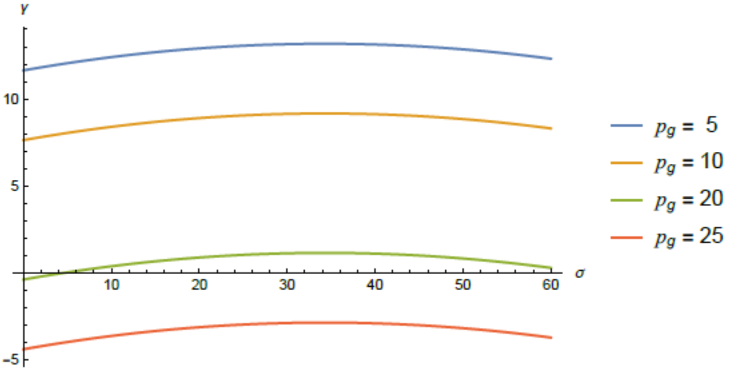

FIGURE – Payment of CCfD in Europe.