# 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

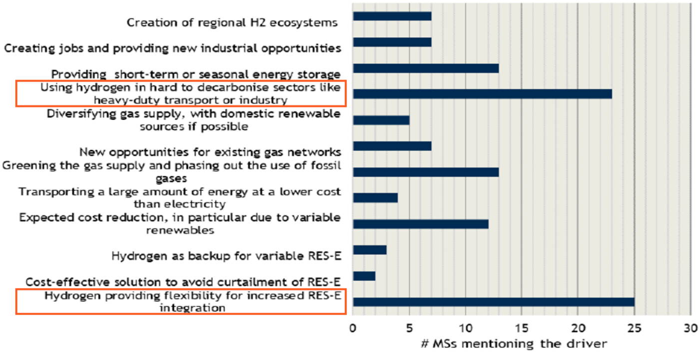


FIGURE – The main benefits expected by Member States from the development of low-carbon hydrogen, FCH2JU (2020)

# Context

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

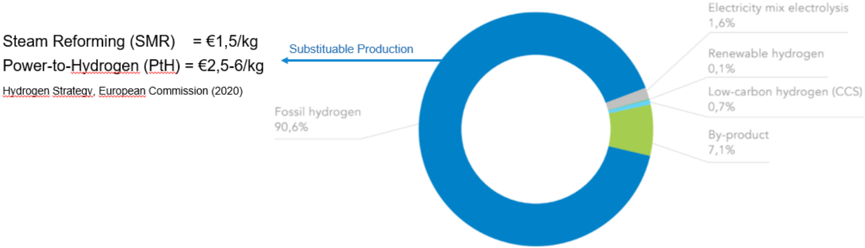


FIGURE – Distribution of $H_2$ production by technology in Europe in 2018, Hydrogen Europe (2020)

# Context

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

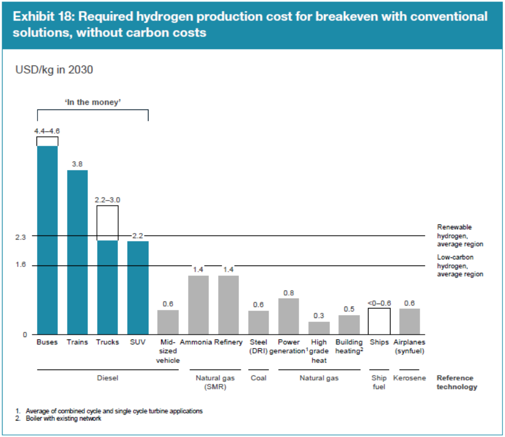


FIGURE – Low-carbon $H_2$ costs needed to achieve competitiveness without carbon price, Hydrogen Insights (2021)

# Contexte

## The CCfD, a tool that arouses interest

- **European Commission** :
  - *A hydrogen strategy for a climate-neutral Europe*, 2020
  - *EU-ETS revision proposol - COM 551 final*, 2021
- **Germany** : *The National Hydrogen Strategy*, 2020
- **Netherlands** : *SDE++ 2020 Stimulation of Sustainable Energy Production and Climate Transition*, 2020.

# Literature

## A tool first described by Helm and Hepburn, 2005

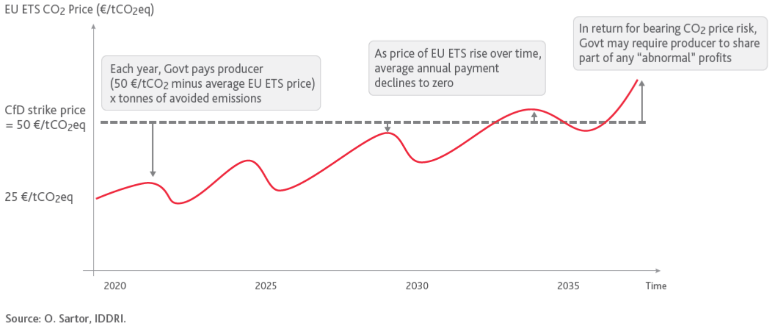


FIGURE – Example of how CCfD works to support the development of low-carbon investments

# Literature

## A tool with multiple advantages

### A hedging tool for low-carbon innovations

- Hedging on *dammage* and *variable costs* risks (Jeddi et al, 2021)
- Lowering the required $CO_2$ price (Richstein & Neuhoff, 2020)
- Closing the funding gap (Richstein 2017)
- Time consistency (Chiappinelli & Neuhoff, 2020)

### An attractive tool due to its political feasibility

- Low policy cost (Chiappinelli & Neuhoff, 2020)
- Consistency with political framework (Sartor & Bataille, 2020)

# A tool with understudied characteristics

## CCfD main characteristics

- Contract type
- Duration
- Payment periodicity
- Abatement amount
- Allocation method
- *Strike* & payment

## Research Question

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

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# 1- General framework : A technological choice between SMR and PtH

## Hydrogen, a self-consumed product

Currently, 2/3 of hydrogen production is self-consumed (Hydrogen Europe, 2020).

**Hyp :** $D_i = q_i$

## A choice based on the difference in marginal costs

For producer-consumers to switch from steam reforming to electrolysis, the costs of electrolysis must be at most equal to those of steam reforming.

**Hyp** : Transportation, storage and purification costs are neglected.
**Hyp** : SMR marginal costs are lower than PtH ones.

# 2- marginal costs specification

Let $i = \{e, s\}$, $p_i$ be the price of energy used by technology $i$, $\rho_i$ be the yield of $i$, both known and constant over the CCfD duration and $\sigma$ be the market price of $CO_2$.

## Marginal cost of $H_2$ by steam reforming

$$c_s(\sigma, p_g) = p_g \rho_s + e_s \sigma. \tag{1}$$

## Marginal cost of $H_2$ by electrolysis

$$c_e(\sigma, p_g) = p_e(\sigma, p_g)\rho_e, \tag{2}$$

$$p_e(\sigma, p_g) = p_0 + p_1\sigma + p_2\sigma^2 + p_3 p_g, \tag{3}$$

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

# 2- marginal costs specification

## With State Aids

### Indirect carbon cost offset

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

$$c_e^{\chi}(\sigma) = c_e(\sigma) - \chi(c_e(\sigma) - c_e(0)). \quad (4)$$

### 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

$$c_s^a(\sigma, p_g) = p_g \rho_s + (e_s - a)\sigma. \quad (5)$$

# 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 :

$$\gamma^{\chi,a}(\sigma) = c_e^{\chi}(\sigma) - c_s^{a}(\sigma). \tag{6}$$

### Definition of the threshold gas price

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

$$-\frac{(e_s - a)^2 - 2p_1(e_s - a)\rho_e(1-\chi)}{4p_2\rho_e(\rho_g - p_3\rho_e)(1-\chi)} + \frac{\rho_e^2(p_1^2(1-\chi) - 4p_0p_2)}{4p_2\rho_e(\rho_g - p_3\rho_e)}. \tag{7}$$

# 3- CCfD strike and payment determination

## CCfD efficiency condition

### Proposition

1. If $p_g > \bar{p}_g^{\chi,a}$ then for all $\sigma$, $\gamma^{\chi,a}(\sigma, p_g) < 0$ i.e. there is no need to set up a CCfD.
2. If $p_g = \bar{p}_g^{\chi,a}$, then the equation 6 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 :

$$\bar{\sigma}_m^{\chi,a} = \bar{\sigma}^{\chi,a} - \frac{\Gamma_1}{\Gamma_2}, \tag{8}$$

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

where $\Gamma_1 =$

$$\sqrt{(e_s - a - p_1\rho_e(1-\chi))^2 + (4p_2\rho_e(-p_0\rho_e + p_g(\rho_g - p_3\rho_e)))(1-\chi)} \tag{10}$$

$$\Gamma_2 = -2p_2\rho_e(1-\chi). \tag{11}$$

# 3- CCfD strike and payment determination

## CCfD payment $\gamma$

### The CCfD payment formula

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

$$\gamma^{\chi,a}(\sigma) = c_e^{\chi}(\sigma) - c_s^{a}(\sigma). \tag{12}$$

### Theorem

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

$$\Gamma_1(\bar{\sigma}_M - \sigma) - \frac{\Gamma_2}{2}(\bar{\sigma}_M - \sigma)^2 = -\Gamma_1(\bar{\sigma}_m - \sigma) - \frac{\Gamma_2}{2}(\bar{\sigma}_m - \sigma)^2 \tag{13}$$

where $\Gamma_1$ and $\Gamma_2$ are defined by (10) and (11).

# 3- 3- CCfD strike and payment determination

## Payment properties

### Propertiess

The CCfD payment verifies the following properties

If $\sigma \in [\bar{\sigma}_m; \bar{\sigma}_M]$ then $\gamma^{\chi,a}(\sigma) \geq 0$.

If $\sigma \notin [\bar{\sigma}_m; \bar{\sigma}_M]$ then $\gamma^{\chi,a}(\sigma) < 0$.

### Consequencies

A positive payment is a form of government subsidy, while a negative payment is a form of producer reimbursement.

# 4-A long-term contract

## A surplus possibility for PtH producers

### Divergence between reference values and market values

During the term of the contract, there may be a discrepancy between the reference values and the market values, in which case :

$$c_e^{\chi}(\sigma, p_g) - \gamma^{\chi,a}(\sigma) \neq c_s^a(\sigma, p_g). \tag{14}$$

### $S_i$ the $i$ producer surplus at $t$

$$S_i(\sigma, p_g) = (c_s^a(\sigma, p_g) - c_e^{\chi}(\sigma, p_g) + \gamma^{\chi,a}(\sigma))q_i \tag{15}$$

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# 1- Data : Electricity prices

$$p_e = p_1\sigma + p_2\sigma^2 + p_3 p_g + \epsilon, \quad (16)$$

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

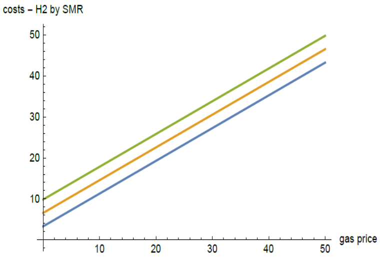
TABLE – Linear regression results for the French (top) and German (bottom) cases. Data : CRE, Observatoire des Marchés, 2010-2019

# 1- Data : other parameters

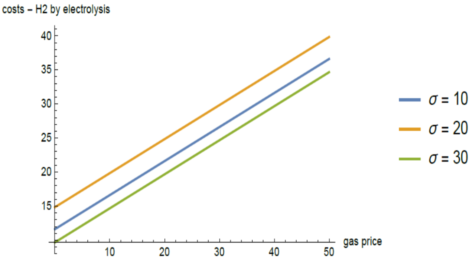
| $\rho_g$ | $e_v$ | $\rho_e$ | a | $\chi$ |
|---|---|---|---|---|
| 80% | 0,328g$CO_2$/MWh | 50% | 0 | 0 |

TABLE – Reference values of the model parameters.

# 2- Analysis of hydrogen production costs



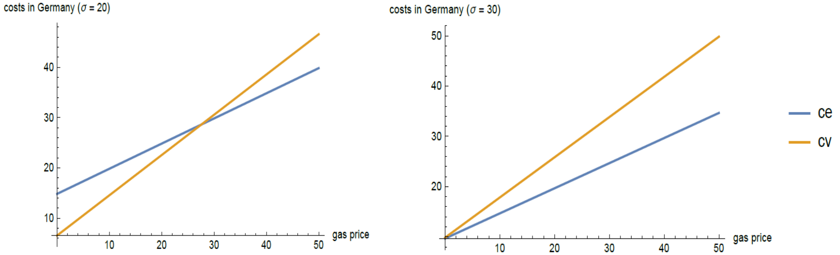

Steam reforming marginal costs




Electrolysis marginal costs

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

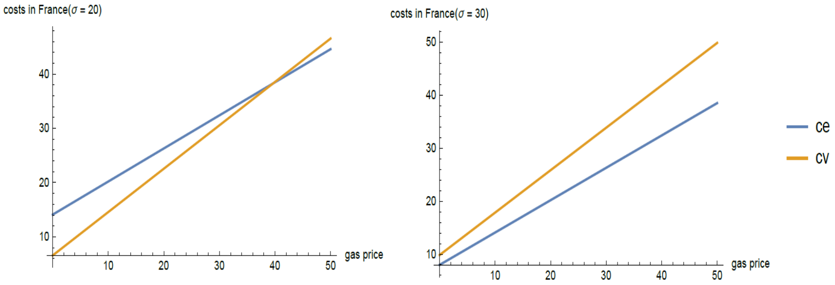
# 2- Analysis of hydrogen production costs




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)*

# 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 France (€/MWh).
*(blue = electrolysis, yellow = steam reforming)*

# 2- Analysis of hydrogen production costs

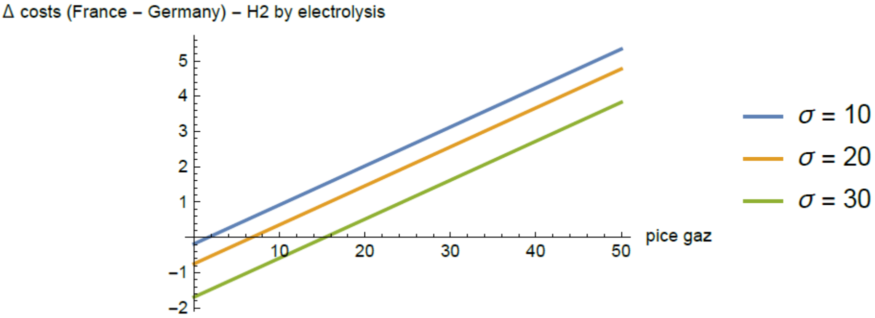



FIGURE – Difference in marginal costs of hydrogen production by electrolysis between France and Germany (€/MWh).

# 3- Analysis of the CCfDs price and payment characteristics

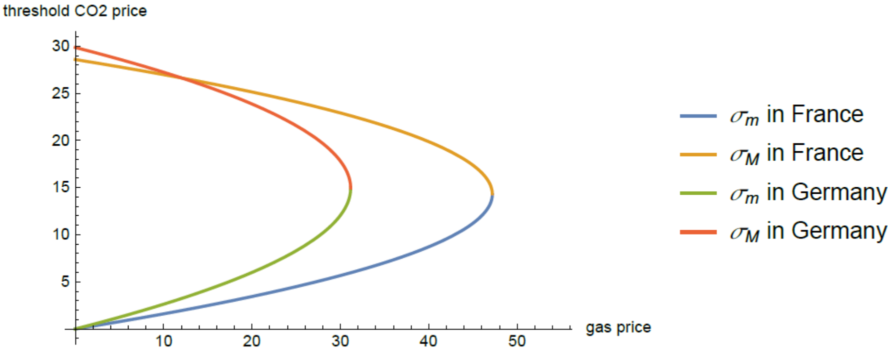



FIGURE – CCfD strikes (€/t) in France and Germany as a function of gaz price (€/MWh).

# 3- Analysis of the CCfDs price and payment characteristics

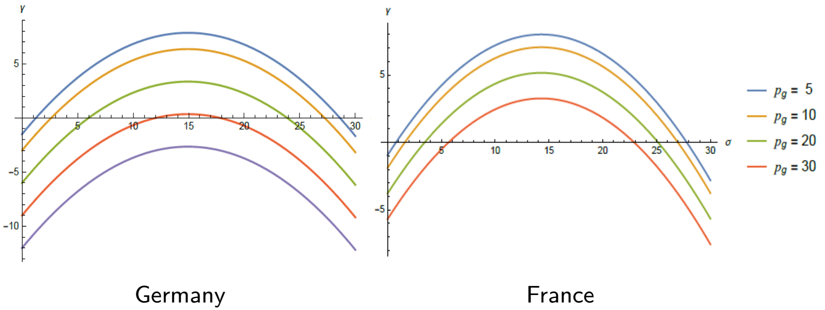
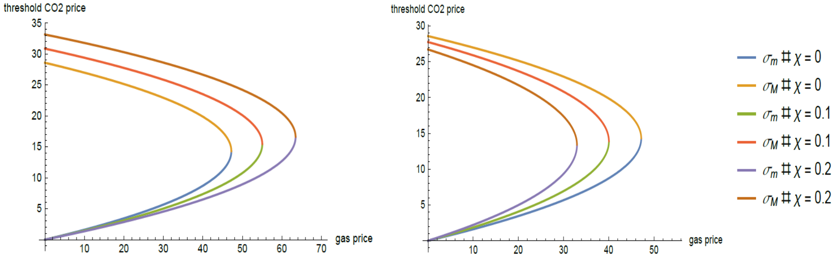



FIGURE – CCfD payment (€/MWh) in France and Germany according to the carbon market price (€/t).

# 3- Analysis of the CCfDs price and payment characteristics




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

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 ;
- The inputs prices should be considered. For instance,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 ;
- CCfDs should include a reimbursement phase to avoid windfall profit.

# Conclusion

## Further research

- Consideration of the whole business plan : LVCOH, risk coverage [ongoing work] ;
- Study of allocation methods ;
- Interactions with EU-ETS prices : opposite effects between price decrease due to decarbonization and price increase due to electrification.

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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 |
| $\sigma$ | 2,25 | 1,37 | 1,64 | 0,11 |
| $\sigma^2$ | -0,06 | 0,05 | -1,22 | 0,23 |
| $p_g$ | 1,21 | 0,25 | 4,76 | 3,71e-05 |
| $\sigma$ | 3,57 | 1,07 | 3,32 | 0,00219 |
| $\sigma^2$ | -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)*

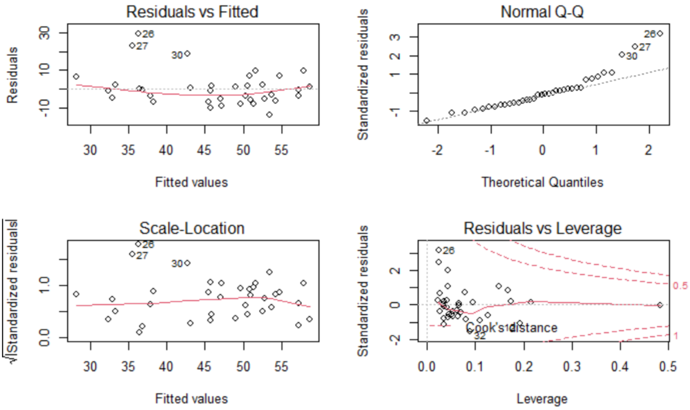


FIGURE – Model residuals for the French case with the complete database.

## 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

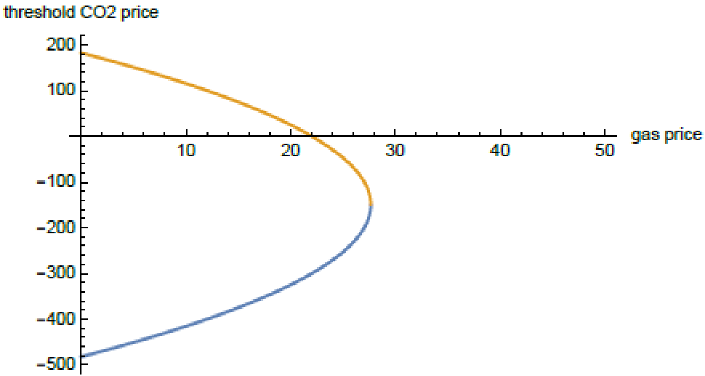


FIGURE – CCfD strike in Europe.

# B.2- Strike and payment for the European case

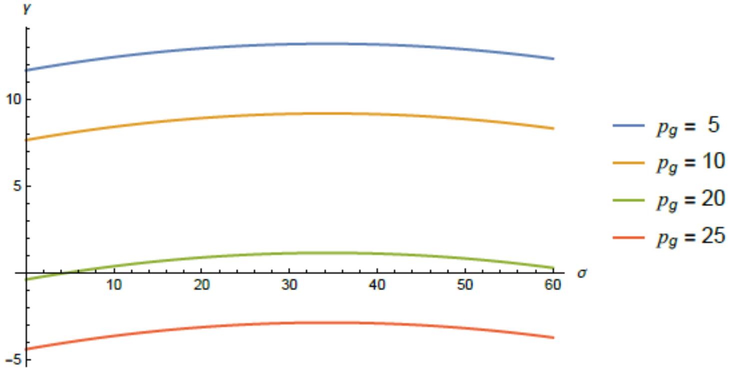


FIGURE – Payment of CCfD in Europe.