Incentives for early adoption of carbon capture technology: further considerations from a European perspective

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Abstract

This note details two comments on a recent policy proposal in Comello and Reichelstein (2014) aimed at favoring the early adoption of Carbon Capture (CC) technology in the next generation of thermal-based power plants to be installed in the United States. First, we examine the implications of a worst-case scenario in which no new CC is adopted internationally beyond what is in place in 2014. Second, we show the potential, under the original proposed subsidy, for the emergence of coordination failures capable of hampering the desired early CC deployment. We propose and evaluate modified schedules of tax-credits sufficient to overcome these concerns. These additions strengthen the argument in the original article: namely, though higher incentive levels are necessary, our findings confirm that the cost of the proposed policy is not out of reach.

Keywords: Tax incentives, Carbon Capture and Storage, Learning effects, Levelized cost, Coordination failure.

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Introduction

The prohibitively high cost of Carbon Capture (CC) technology for first-of-a-kind plants is recurrently cited as a major barrier to its large-scale deployment. To overcome this problem, Comello and Reichelstein (2014) recently articulate an innovative policy proposal to enable substantial cost reductions by leveraging the sizeable deployment of thermal-based power generation projected in the U.S. during the period 2017-2027. The proposal combines two ingredients: a binding and inflexible emission standard; and the "*Accelerated Carbon Capture Deployment*" (ACCD) – a preannounced schedule of Investment Tax Credits (ITC) and Production Tax Credits (PTC) – aimed at providing an incentive for newly built power plants in the U.S. to adopt CC immediately.

This note extends the analysis by considering two issues. In a first section, we apply the framework detailed in the original article[1] to generate a schedule of tax-credits that is robust to alternative scenarios for CC deployments outside the U.S. In a second section, we reflect on the possible emergence of a coordination game capable of hampering the desired early deployment of that technology and propose a modified schedule of tax-credits that is sufficient to overcome that problem.

1 – The role of early CC deployments outside the U.S.

Using a list of proposed but still undecided projects (GCCSI, 2013), the authors assume the installation of nearly 3 GW of foreign CC capabilities between 2014 and 2020. However, in Europe, the funding of large CC projects has recently proven to be difficult, causing delays and several project cancelations (Lupion and Herzog, 2013). As early foreign projects are posited to engender international spillovers, one may wonder whether these withdrawals could undermine the proposal's success.

To render the proposal robust to the vicissitudes impacting foreign projects, we consider a 'worst-case' scenario whereby foreign deployments are restricted to the unique Canadian 130MW power plant finalized in 2014. To compensate for the absence of foreign early investments, augmented ITC and PTC schedules are needed (cf., Figure 1) but this robust version is almost as attractive as the initial version (cf. Table 1).[2]

[INSERT FIGURE 1]

[1] The two authors must be praised for having made their data and spreadsheet model readily available to readers.

[2] For the sake of brevity, this note solely summarizes our main conclusions. Further details on the methods used to generate the results are provided in a Supporting Document to be disseminated as a companion file to this paper.

Table 1. The main findings obtained under the robust scenario

The key findings
• The Levelized Cost of Electricity (LCOE) obtained with a facility that becomes operational by the end of 2027 is approximately 7.9 ¢/kWh if CC technology is consistently adopted by all the newly built U.S. thermal power plants.[(a)]   • The magnitude of the tax-credit levels remain politically acceptable (cf., Figure 1).   • Overall, the cumulated undiscounted foregone tax revenue to the U.S. Treasury reaches about \$8.2 billion.[(b)] This robust schedule of incentives thus represents a cost-effective solution for achieving a large scale deployment of this innovative technology.

Note: (a) This figure remains close to the 7.8 ¢/kWh obtained in the original article (Comello and Reichelstein, 2014 - Finding 3); (b) This 25% increase over the base-case scenario reveals the positive externality provided by foreign early investments in first-of-a-kind CC plants.

2 – Strategic interactions among CC adopters

Recent European literature on CC and storage has highlighted the interactions that exist among CC adopters connected to a common infrastructure system (Mendelevitch, 2014; Massol, et al., 2015). In the present paper, infrastructure issues are neglected but the use of an experience curve *de facto* generates some interactions. It is instructive to examine these interactions further.

A – Notation

To begin, we introduce our notation. We consider a given year t in $\{2017,...,2027\}$ and let: K_t denote the total planned capacity of all the power plants to be started during that year; and CK_t denote the cumulated CC capacity of all the plants installed during the preceding years τ with $\tau < t$.[3]

For an investor that considers installing a power plant during that year, we let: c_t^R denote the LCOE obtained in case of a 'last-minute retrofit' by the end of 2027,[4] and $c_t^N(x)$ be the continuous and

[3] By construction, CK_t is thus equal to $CK_t = CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$ if CC technology was systematically deployed at its maximum potential during each of the preceding years.

[4] As all power plants installed between 2017 and 2027 are forced to adopt CC by the end of that year, this LCOE figure is systematically evaluated assuming that $CK_{2017} + \sum_{\tau=2017}^{2027} K_\tau$ is the cumulated CC capacity in operation at that time.

strictly decreasing function that gives the LCOE if that plants adopts CC immediately given x, the cumulated CC in operation at that date.[5] The condition $c_t^R < c_t^N(x)$ is assumed to hold for any x with $x \le CK_{2017} + \sum_{\tau=2017}^{t} K_\tau$ indicating that, absent any subsidy, it is less costly to delay the adoption of CC capabilities.

In year t, we do not model the tax-credits but simply assume that their effect is to lower the LCOE measured on a power plant that early adopts CC capabilities. We let S_t be the levelized subsidy and $\tilde{c}_t^N(x) := c_t^N(x) - S_t$ denote the subsidized LCOE function.

B – The subsidy scheme in Comello and Reichelstein (2014)

We now review the evaluation of the schedule of tax-credits used in the original policy proposal. Recall that the ACCD tax-credits are set so that, for a facility to be installed in a given year, it becomes advantageous to adopt CC capabilities immediately compared to retrofitting that plant by the end of 2027. The evaluation of the schedule of tax-credits presented in the original paper is detailed in an associated spreadsheet model: the "NGCC + CC Calculator" (Comello and Reichelstein, 2014). In this model, CC adoption at the maximum level is assumed in each year before t. The tax-credits are calibrated so that S_t, the levelized subsidy implemented in year t, verifies $S_t \ge \underline{S}_t$, where $\underline{S}_t$ is the threshold level:[6]

$$\underline{S}_t := c_t^N\left(CK_t + K_t\right) - c_t^R, \quad \text{obtained with} \quad CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau . \tag{1}$$

This threshold is evaluated assuming that all the plants installed during the preceding years have early adopted CC capabilities.

The authors underline that, by construction, the tax-credits prevent possible 'deviation' from an 'equilibrium path' of early CC adoption. Indeed, one can model CC adoption as a sequence of 11 irrevocable decisions whereby, in each year, a single decision-maker: (i) controls the capacity K_t, (ii) faces a binary choice with respect to the early adoption of CC capability, and (iii) is posited to have full information on the learning curve so that he knows how his own decision modifies the LCOE incurred in case of early adoption. Within this framework, the proposed schedule of tax-credits in the

[5] In the original paper, the effects of learning are allowed to commence only after 3GW of cumulative CC capacity has been deployed. Thus, $c_t^N(x)$ is a constant if $x < 3$ GW and is a continuous and strictly decreasing function if $x \ge 3$ GW. The discussion hereafter therefore concentrates on this second case.

[6] This definition of the threshold level has been derived from a meticulous examination of the original "NGCC + CC Calculator". A document summarizing this analysis and explaining how this threshold can be traced back in the original spreadsheet model can be obtained from the authors upon request.

original article is such that adoption is decided in each year and thus provides the desired policy outcome.

C – Is that proposed subsidy sufficient?

However, the capacity forecasts and the standard plant size used by the authors together suggest that several power stations will be installed in some years (particularly during the period 2023 – 2027). As these plants are likely to be owned by independent companies, one may wonder whether, in each year t, the threshold level $\underline{S}_t$ is sufficient to induce the joint early adoption of CC capability by all players.

To address this issue, one has to examine the strategic interactions among these investors. We focus on a given year t and assume that early CC adoption has systematically been achieved during the preceding years so that $CK_t = CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$. We consider the situation whereby K_t the projected capacity addition in year t is shared among $n > 1$ independent players. Each player i controls a fraction α_i of that capacity with $0 < \alpha_i < 1$ and $\sum_{i=1}^{n} \alpha_i = 1$.

Each player has to make an irrevocable decision regarding the immediate installation of CC capabilities. The decision has a binary nature and we let $\delta_i \in \{0,1\}$ denote the decision of player i, where $\delta_i = 1$ (respectively 0) indicates the early (respectively delayed) adoption of CC capabilities. The objective of each player is to <u>minimize</u> its LCOE.

As in the original "NGCC + CC Calculator", we assume that each player knows how the LCOE incurred in case of early adoption is modified by the capacity decided at that time. Thus, under these assumptions, the LCOE incurred by a player i is as follows:

- If 'delayed adoption' is chosen by that player (i.e., $\delta_i = 0$), he incurs c_t^R.

- If that player decides to early adopt CC capabilities (i.e., $\delta_i = 1$), he incurs the subsidized LCOE $\tilde{c}_t^N \left(CK_t + \alpha_i K_t + \sum_{\substack{j=1 \\ j \neq i}}^{n} \delta_j \alpha_j K_t \right)$ which is a function of the other players' decisions in year t.

We now present a series of findings derived from the analytical developments detailed in a Supporting Document to this paper.[7] To begin, we assume that the levelized subsidy S_t is chosen so as to verify $S_t \geq \underline{S}_t$, where $\underline{S}_t$ is the threshold level considered in the original "NGCC + CC Calculator".

Finding 1 – Any levelized subsidy S_t with $S_t \geq \underline{S}_t$, where $\underline{S}_t$ is defined in (1), is sufficient to make the strategy vector stating 'early CC adoption' for every player a pure strategy Nash Equilibrium (NE).

This finding conveys an important result as it shows that the condition $S_t \geq \underline{S}_t$, where $\underline{S}_t$ is defined as above, is sufficient to make "generalized early adoption" a NE. Sadly, the proposition below indicates that such a subsidy is not sufficient to obtain the uniqueness of that NE.

Finding 2 – The condition $S_t \geq \underline{S}_t$ where $\underline{S}_t$ is defined in (1), is not sufficient to make the strategy vector stating 'early CC adoption' for every player the unique NE.

Together, these two findings suggest that implementing a levelized subsidy that solely verifies $S_t \geq \underline{S}_t$ could lead to a coordination game with possibly several NEs.

The selection of a NE where some emitters rationally prefer to delay CC adoption in year t is a source of concern from both a static and a dynamic perspective. From a static perspective, such an equilibrium *de facto* implies that early CC adoption is not achieved at the desired level K_t. From a dynamic perspective, the following finding indicates that this lower-than-expected level of early CC adoption in year t may also have adverse consequences on the decisions to be taken in subsequent years because the proposed levelized subsidy proposed in year $t+1$ may no longer be large enough to achieve generalized early CC adoption.

Finding 3 – Possible existence of a "snowball" effect: If delayed adoption were to be decided by some players in year t, a levelized subsidy S_{t+1} that verifies the condition $S_{t+1} \geq \underline{S}_{t+1}$, where $\underline{S}_{t+1}$ is the threshold value defined in (1) for year $t+1$,[8] is not sufficient to make the strategy vector stating 'early CC adoption' for every player in year $t+1$ a pure strategy NE.

[7] For the sake of brevity, all formal proofs are provided in this Supporting Document.

[8] That is $\underline{S}_{t+1} := c^N_{t+1}\left(CK_{t+1} + K_{t+1}\right) - c^R_{t+1}$ which is evaluated assuming that generalized early CC adoption has been attained during all the preceding years, i.e., $CK_{t+1} := CK_{2017} + \sum_{\tau=2017}^{t} K_\tau$.

D – A remedy

Because such coordination failures may jeopardize the desired policy outcomes, one may desire that the schedule of levelized subsidies rules out any possibility for the investors in any given year t to pick up a NE that does not lead to generalized early CC adoption.

Proposition – In each year t, any tax-credit yielding a levelized subsidy S_t that verifies $S_t \geq \overline{S}_t$, with $\overline{S}_t := c_t^N\left(CK_t\right) - c_t^R$ and $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$, is sufficient to make the strategy vector stating 'early CC adoption' for every player the unique NE.

As $\overline{S}_t > \underline{S}_t$, the condition $S_t \geq \overline{S}_t$ is more restrictive than the one considered in the original article. Nevertheless, one should note that this proposition holds for any number of players and any repartition of the capacity among them, which makes it preferable to opt for that larger threshold level.[9]

E – Application

This subsection reports the results obtained using the threshold $\overline{S}_t$ under two capacity deployment scenarios: the original one (cf., Figure 2) and the robust one discussed in Section 1 (cf., Figure 3).[10]

Our evaluations indicate that the magnitude of the ITC levels remains similar; however, augmented PTC are needed. Under the original scenario, strictly larger expenditures for the U.S. Treasury are needed in each year which confirms that the incentives in the original article are not sufficient to obtain the desired unique equilibrium (cf., Figure 2.C). In case of a robust deployment scenario, substantially increased PTC rates are needed to guarantee the uniqueness of the NE (cf. Figure 3.B.).

[INSERT FIGURE 2]

[INSERT FIGURE 3]

Table 2 summarizes the cumulative (undiscounted) foregone tax revenue to the U.S. Treasury under the four policy options obtained by combining the two capacity deployments scenarios with the two thresholds. *Ceteris paribus*, the cost increase generated by solely one of two effects discussed in this paper (i.e., a robust capacity deployment scenario with the original methodology, or our revised methodology with the original scenario) remains modest. In contrast, the joint presence of these two

[9] In contrast, the demonstration in a Supporting Document to this paper formally proves that, in case of a levelized subsidy S_t that verifies $\underline{S}_t \leq S_t < \overline{S}_t$, there exists at least one industrial configuration (i.e., a number of players and a distribution of the capacity K_t among them) such that the NE stating 'early CC adoption for every player in year t' is not unique.

[10] For the sake of brevity, this note solely summarizes our main conclusions. Further details on the methods used to generate the results are provided in a Supporting Document to be disseminated as a companion file to this paper.

effects generates a substantial increase in the cost of that policy: about $14.1 billion. This is a 113% increase over the $6.6 billion figure obtained in the original article. Nevertheless, we believe that this cost figure remains tolerable for such an ambitious policy that would now be rendered robust to both foreign adverse events and domestic gaming issues.

Table 2. The cumulative foregone tax revenue to the U.S. Treasury under the four various situations ($ billion)

		Methodology used to determine the tax credit schedule	
		Original $S_t \geq \underline{S}_t$	"Unique NE" $S_t \geq \overline{S}_t$
CC capacity deployment scenario	Original	6.6 *	8.9
	"Robust"	8.2 **	14.1

*Note: "Robust" refers to the CC capacity deployment detailed in Section 1 and "Unique NE" refers to the new methodology discussed in Section 2.D. The asterisks * and ** respectively indicate the policy discussed in Comello and Reichelstein (2014) and the incentive policy presented in Section 1.*

Conclusions

This note discusses the feasibility of the policy proposal in Comello and Reichelstein (2014). Two lines of arguments have been considered. First, we have examined the effects of early CC deployments outside the U.S. Second, we have determined that the original ACCD schedule can be insufficient to engender the desired generalized early adoption of CC capabilities because of the possible co-existence of multiple Nash equilibria. In both cases, an appropriately modified incentive policy has been proposed and calibrated to overcome those issues. Though higher incentive levels are obtained, our findings confirm that the cost of the revised ACCD policy to the U.S. Treasury is not out of reach. This modified policy thus represents an interesting instrument to break the 'vicious circle' that currently hampers the deployment of CC technologies.

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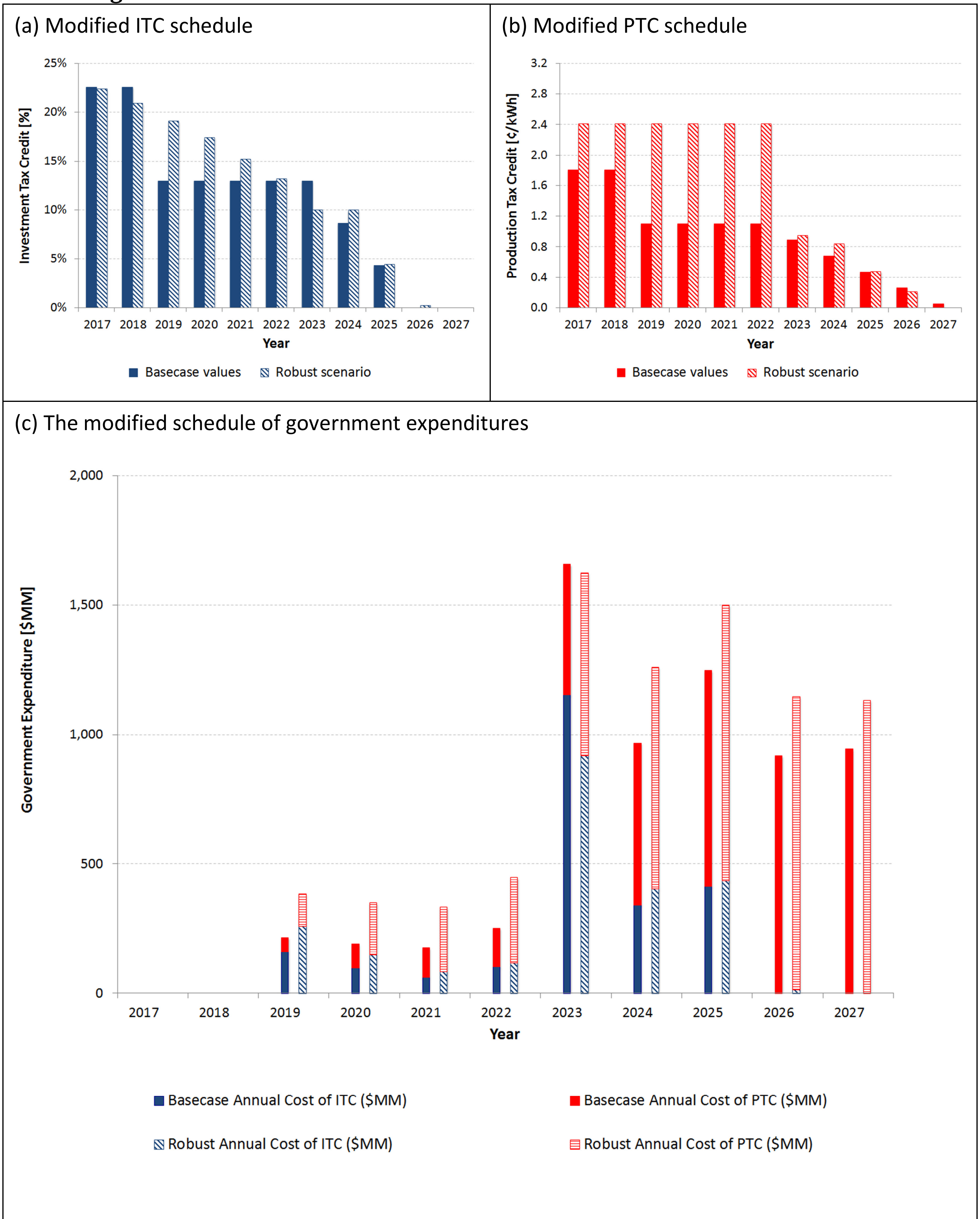
APPENDIX

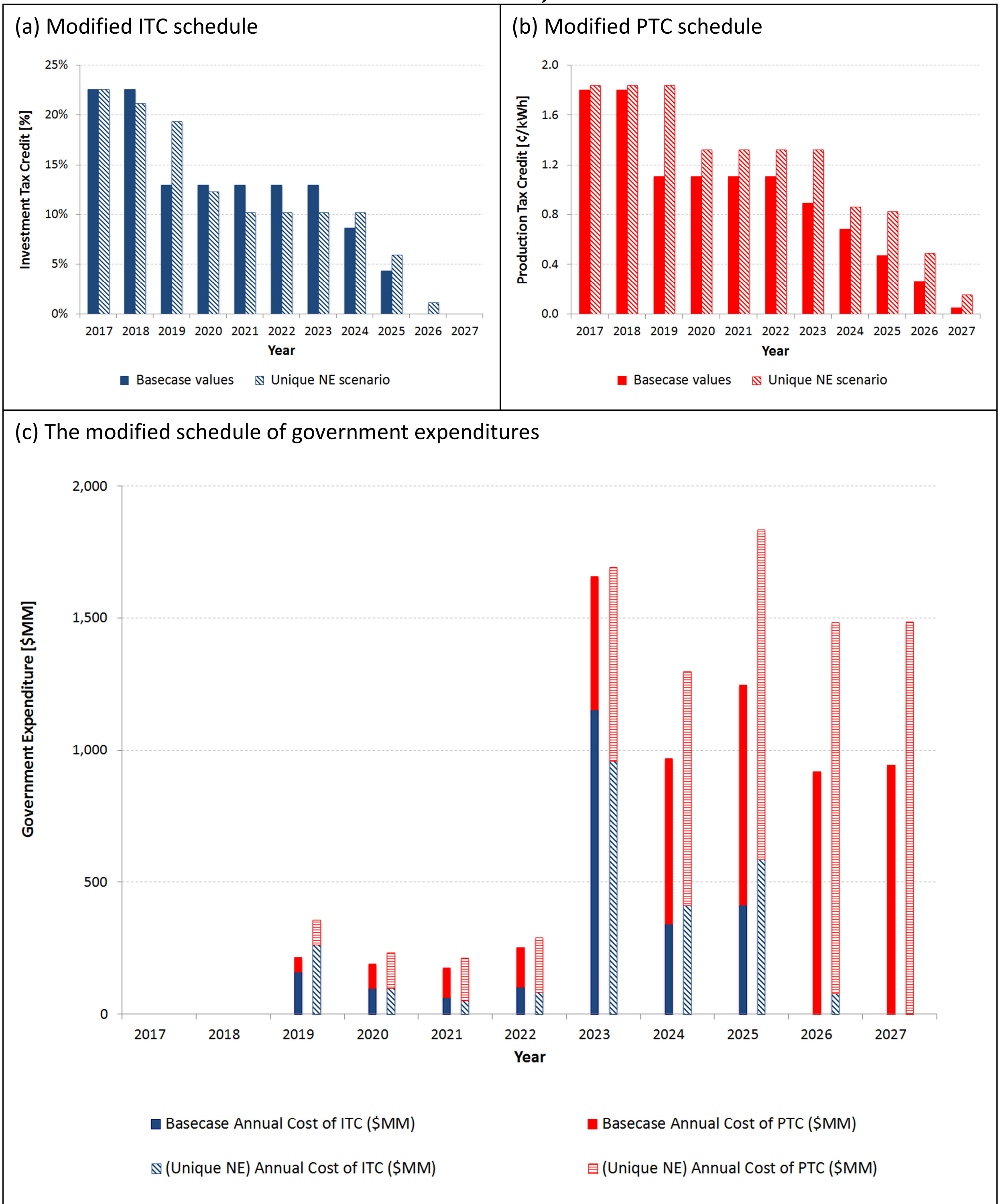
Cf. the companion document.

Figure 1. The modified ACCD tax credits schedule under a robust scenario



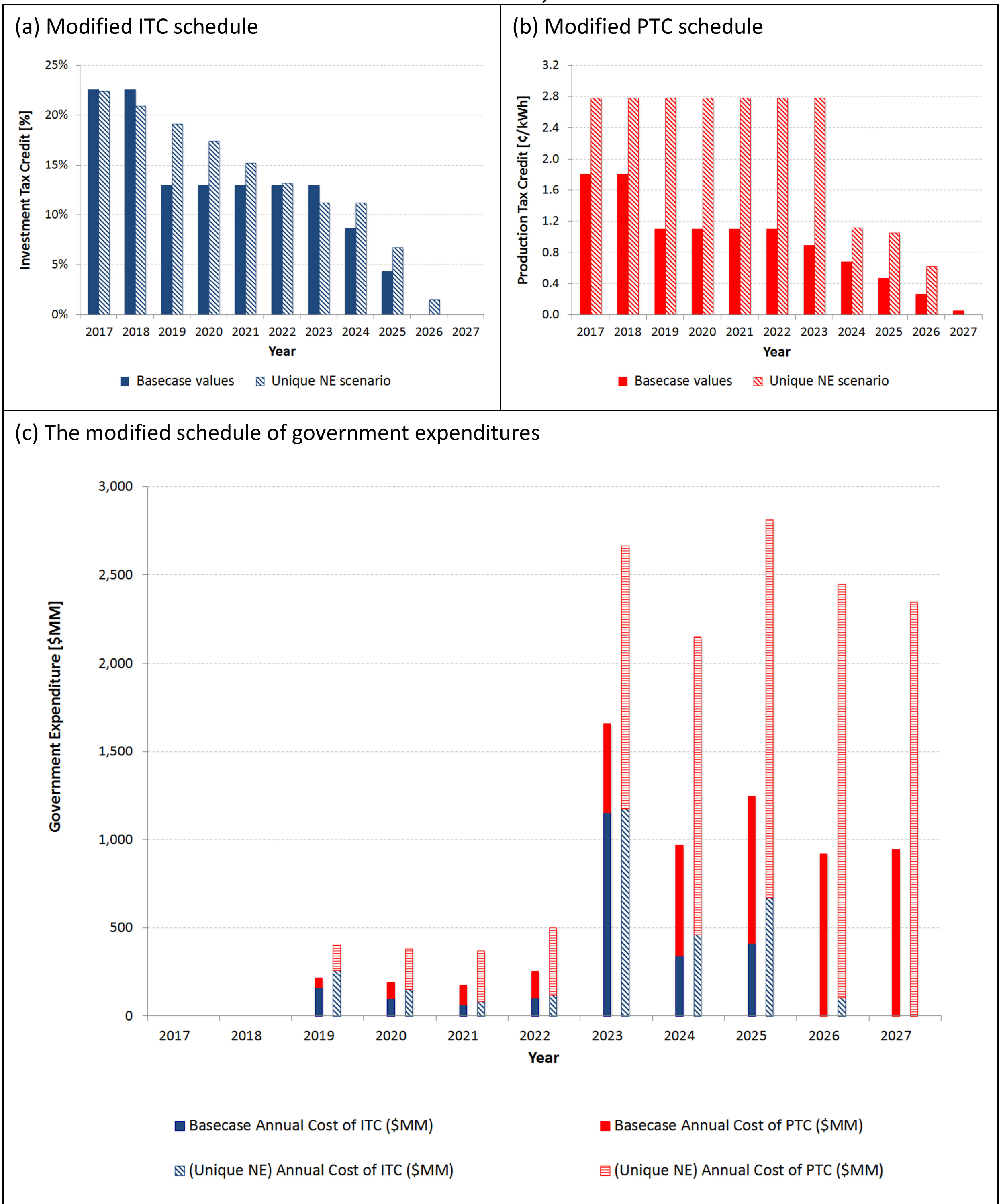
Note: These graphs compare the basecase values in the original policy proposal with the values needed in case of a robust deployment scenario. The methodology retained to evaluate these values is the one retained in the original article.

Figure 2. The tax credit schedule needed to obtain a unique NE (original deployment scenario)



Note: These graphs compare the basecase values in the original policy proposal with the values needed to obtain a unique NE under the high CC capacity deployment scenario (i.e., the construction of nearly 3 GW of foreign CC capabilities between 2014 and 2020).

Figure 3. The tax credit schedule needed to obtain a unique NE (robust deployment scenario)



Note: These graphs compare the basecase values in the original policy proposal with the values needed to obtain a unique NE under the robust CC capacity deployment scenario discussed in Section 1.

Supporting Document:

Incentives for early adoption of carbon capture technology:

Further considerations from a European perspective

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This document constitutes a technical appendix to the aforementioned paper.

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Appendix A – The role of non-U.S. CC adoptions, a sensitivity analysis

This Appendix details the assumptions, methodology and results commented in Section 1.

A.1 Assumptions

Table A.1 details the projected annual capacity deployments by year retained in the 'worst case' scenario. This conservative projection has been derived from Comello and Reichelstein (2014, Supporting document - Table A.1.) by restraining the amount of international capacity to the unique 130 MW Carbon Capture (CC) power plant that is currently in operation in Canada. Capacity deployment excepted, our assumptions are the ones discussed in the original article.

Table A.1. Projected U.S. Capacity Deployments of NGCC Facilities and International Capacity Deployments of Carbon Capture Technology in the Robust Scenario

Year	Projected Annual Int'l Additions of Capture Unit Capacity (GCCSI) [MW]	Projected Annual Capacity Additions 2017-2027 (EIA) [MW]	Total Annual Capacity Additions [MW]	Total Cumulative Capacity Additions [MW]	Projected Net NGCC Capacity 2017-2027 (EIA) [MW]
2014	130		130	130	189 939
2015	0		0	130	192 122
2016	0		0	130	192 447
2017	0	0	0	130	192 447
2018	0	0	0	130	192 220
2019	0	690	690	820	192 910
2020	0	432	432	1 252	193 342
2021		272	272	1 524	193 615
2022		450	450	1 974	194 064
2023		5350	5 350	7 324	199 414
2024		2389	2 389	9 712	201 803
2025		5907	5 907	15 619	207 710
2026		4307	4 307	19 926	212 017
2027		6828	6 828	26 754	218 845

A.2 Methodology

We proceed as in Comello and Reichelstein (2014) and identify the minimum incentives required to bridge the gap between: (i) the Levelized Cost of Electricity (LCOE) of a facility that is retrofitted in 2027, and (ii) the LCOE of a plant that immediately adopts CC capabilities. For each year, the minimum investment tax credit (respectively production tax credits) is calibrated so that the levelized capacity (respectively variable) cost in case of immediate CC adoption[1] is equal to those incurred in case of a retrofit in 2027.[2]

A.3 Results

In Table A.2, we detail the "Accelerated Carbon Capture Deployment" (ACCD) tax credits obtained in the robust scenario.

[1] For the sake of comparability, this levelized cost is determined using the fiscal depreciation schedules and the 10% first-of-a-kind premium defined in Comello and Reichelstein (2014).

[2] Note that these minimum tax credits schedule are not necessarily tiered. The use of different fiscal depreciation schedules between two successive years can generate a situation whereby the investment tax credit needed in a given year is larger than that needed during the previous year. To overcome that issue, we proceed as in the NGCC+CC Calculator and generate tiered schedules. In this paper, a linear programming approach is implemented to obtain these tiered schedules. The linear program is aimed at determining the tiered tax credit schedule that minimizes the cumulative foregone tax revenue to the U.S. Treasury and verifies two types of constraints: (i) the tiered tax credit in a given year must not be lower than that of the subsequent year, and (ii) the tiered tax credits must not be lower than the minimum values required for the LCOE of a new plant to be lower than the LCOE of a plant retrofitted in 2027.

Table A.2. The ACCD tax credits in the Robust Scenario

Year	Fiscal Depreciation Schedule	Schedule of Investment Tax Credits	Schedule of Production Tax Credits [¢/kWh]
2017	MACRS	22.4%	2.41
2018	MACRS	20.9%	2.41
2019	MACRS	19.1%	2.41
2020	MACRS	17.4%	2.41
2021	MACRS	15.2%	2.41
2022	MACRS	13.1%	2.41
2023	MACRS	10.0%	0.94
2024	150% DB	10.0%	0.84
2025	150% DB	4.4%	0.48
2026	150% DB	0.2%	0.21
2027	150% DB	0.0%	0.00

Note: MACRS indicates that all capital expenditures will be eligible for the five-year accelerated depreciation schedule according to MACRS; 150% DB indicates that all capital expenditures will be subject to the current 150% balance, 20-year depreciation schedule.

Appendix B – Mathematical proofs

This Appendix presents the formal proofs of the results stated in Section 2. Unless otherwise specified, the notation is based on the one introduced in the paper.

Finding 1 – Any levelized subsidy S_t with $S_t \geq \underline{S}_t$, where $\underline{S}_t := c_t^N\left(CK_t + K_t\right) - c_t^R$ and $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$, is sufficient to make the strategy vector stating 'early CC adoption' for every player a pure strategy Nash Equilibrium (NE).

> <u>Proof:</u> *One has to verify whether a player has or not an incentive to deviate from the strategy vector stating* $\delta_i = 1$ *for every player. In case of a deviation from that vector, that player would incur the LCOE,* c_t^R. *In contrast, the subsidized LCOE obtained in case of early adoption is* $\tilde{c}_t^N\left(CK_t + \alpha_i K_t + \sum_{\substack{j=1 \\ j\neq i}}^{n} \delta_j \alpha_j K_t\right)$ *which is equal to* $\tilde{c}_t^N\left(CK_t + K_t\right)$ *with the strategy vector stating* $\delta_i = 1$ *for every player. Interestingly, the subsidized LCOE verifies the condition:* $\tilde{c}_t^N\left(x\right) \leq c_t^N\left(x\right) - \underline{S}_t$. *Replacing the threshold level* $\underline{S}_t$ *by its definition and* x *by the value* $CK_t + K_t$, *the condition* $\tilde{c}_t^N\left(CK_t + K_t\right) \leq c_t^R$ *is verified which indicates that, if every player decides to early adopt the CC technology, each players has no incentive to deviate from that strategy vector. As this condition is verified for each player in the game, the strategy vector* $\delta = \left(1,1,\ldots,1\right)$ *is a pure strategy NE.* *Q.E.D.*

Finding 2 – The condition $S_t \geq \underline{S}_t$ where $\underline{S}_t := c_t^N\left(CK_t + K_t\right) - c_t^R$ and $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$, is not sufficient to make the strategy vector stating 'early CC adoption' for every player the unique NE.

<u>Proof:</u> Let us consider a levelized subsidy S_t^* *that jointly verifies the two conditions:* $S_t^* \geq \underline{S}_t$ and $S_t^* < c_t^N\left(CK_t + K_t \text{ Max}\left\{\alpha_j\right\}_{j\in\{1,\ldots,n\}}\right) - c_t^R$ *. It is possible to find such a level because* $c_t^N(x)$ *is a smooth and strictly decreasing function and* $\alpha_i < 1$ *for any player* i *which together indicate that the interval* $\left[\underline{S}_t, c_t^N\left(CK_t + K_t \text{ Max}\left\{\alpha_j\right\}_{j\in\{1,\ldots,n\}}\right) - c_t^R\right)$ *is nonempty. With that subsidy level* S_t^**, the strategy vector* $\delta = (1,1,\ldots,1)$ *is a NE (cf. Finding 1). Now, let us examine the strategy vector* $\delta = (0,\ldots,0)$ *that states generalized delayed adoption and compare, for each player* i*, the LCOE incurred with that vector (i.e.,* c_t^R*) with the LCOE obtained in case of a unilateral deviation (i.e., the subsidized LCOE* $\tilde{c}_t^N\left(CK_t + \alpha_i K_t + \sum_{\substack{j=1\\ j\neq i}}^{n} \delta_j \alpha_j K_t\right) = \tilde{c}_t^N\left(CK_t + \alpha_i K_t\right)$ *as* $\delta_j = 0$ *for any player* j *with* $j \neq i$*). Using both the definition of the subsidized LCOE* $\tilde{c}_t^N\left(CK_t + \alpha_i K_t\right) = c_t^N\left(CK_t + \alpha_i K_t\right) - S_t^*$ *and the condition* $S_t^* < c_t^N\left(CK_t + K_t \text{ Max}\left\{\alpha_j\right\}_{j\in\{1,\ldots,n\}}\right) - c_t^R$*, the subsidized LCOE verifies the condition:* $c_t^N\left(CK_t + \alpha_i K_t\right) - c_t^N\left(CK_t + K_t \text{ Max}\left\{\alpha_j\right\}_{j\in\{1,\ldots,n\}}\right) + c_t^R < \tilde{c}_t^N\left(CK_t + \alpha_i K_t\right)$*. As* $c_t^N(x)$ *is a strictly decreasing function, the condition* $c_t^N\left(CK_t + \alpha_i K_t\right) \geq c_t^N\left(CK_t + K_t \text{ Max}\left\{\alpha_j\right\}_{j\in\{1,\ldots,n\}}\right)$ *is also verified. Together, the last two conditions indicate that* $c_t^R < \tilde{c}_t^N\left(CK_t + \alpha_i K_t\right)$ *which means that player* i *has no incentive to deviate from the strategy vector* $\delta = (0,\ldots,0)$ *because the associated LCOE is always lower than the subsidized LCOE incurred in case of a unilateral deviation. As this condition holds for any player, the strategy vector* $\delta = (0,\ldots,0)$ *is also a pure strategy NE. Hence, the condition* $S_t \geq \underline{S}_t$ *is not sufficient to make* $\delta = (1,1,\ldots,1)$ *the unique NE.* *Q.E.D.*

Finding 3 – Possible existence of a "snowball" effect: If delayed adoption were to be decided by some players in year t, a levelized subsidy S_{t+1} that verifies the condition $S_{t+1} \geq \underline{S}_{t+1}$, where $\underline{S}_{t+1} := c_{t+1}^{N}\left(CK_{t+1} + K_{t+1}\right) - c_{t+1}^{R}$ and $CK_{t+1} := CK_{2017} + \sum_{\tau=2017}^{t} K_{\tau}$, is not sufficient to make the strategy vector stating 'early CC adoption' for every player a pure strategy Nash Equilibrium (NE) in year $t+1$.

<u>Proof:</u> Because of non-adoption, we assume that the CC capacity constructed in year t attains a level k_t with $k_t < K_t$. In year $t+1$, we consider the strategy vector $\delta = (1,1,...,1)$ and examine the subsidized LCOE obtained by a given player i when early adopting CC capabilities: $\tilde{c}_{t+1}^{N}\left(CK_t + k_t + \alpha_i K_{t+1} + \sum_{\substack{j=1 \\ j \neq i}}^{n} \delta_j \alpha_j K_{t+1}\right) = \tilde{c}_{t+1}^{N}\left(CK_t + k_t + K_{t+1}\right)$. We consider the levelized subsidy $S_{t+1} = \underline{S}_{t+1}$. In that case $\tilde{c}_{t+1}^{N}\left(CK_t + k_t + K_{t+1}\right) = c_{t+1}^{N}\left(CK_t + k_t + K_{t+1}\right) - c_{t+1}^{N}\left(CK_t + K_t + K_{t+1}\right) + c_{t+1}^{R}$. As $k_t < K_t$ and c_{t+1}^{N} is a strictly decreasing function, the subsidized LCOE verifies $\tilde{c}_{t+1}^{N}\left(CK_t + k_t + K_{t+1}\right) > c_{t+1}^{R}$ indicating that this player has an incentive to unilaterally deviate from the strategy vector $\delta = (1,1,...,1)$. Q.E.D.

Proposition – In each year t, any tax-credits yielding a levelized subsidy S_t that verifies $S_t \geq \overline{S}_t$, with $\overline{S}_t := c_t^{N}\left(CK_t\right) - c_t^{R}$ and $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_{\tau}$, is sufficient to make the strategy vector stating 'early CC adoption' for every player the unique NE.

<u>Proof:</u> We assume that a subsidy S_t that verifies $S_t \geq \overline{S}_t$ is implemented. As c_t^{N} is a strictly decreasing function, we can notice that $\overline{S}_t > \underline{S}_t$, which indicates that the subsidy S_t is sufficient to make the strategy vector $\delta = (1,1,...,1)$ a NE (cf. Proposition 1). Now, we concentrate on the uniqueness and assume that there exists a second NE: i.e., a strategy vector δ' with at least one player i deciding to delay the adoption (i.e., $\delta_i' = 0$) that also verifies the conditions for a NE. With that vector, player i incurs the LCOE c_t^{R}. We now examine $\tilde{c}_t^{N}\left(CK_t + \alpha_i K_t + \sum_{\substack{j=1 \\ j \neq i}}^{n} \delta_j' \alpha_j K_t\right)$ the subsidized LCOE that would be incurred by that player i by deviating from the strategy vector δ'. As the individual shares are positive, we have

$CK_t + \alpha_i K_t + \sum_{\substack{j=1 \\ j \neq i}}^{n} \delta'_j \alpha_j K_t > CK_t$. As c_t^N is a strictly decreasing function, the inequality $\tilde{c}_t^N \left(CK_t + \alpha_i K_t + \sum_{\substack{j=1 \\ j \neq i}}^{n} \delta'_j \alpha_j K_t \right) < \tilde{c}_t^N \left(CK_t \right)$ hold. As $S_t \geq \overline{S}_t$, the condition $c_t^N(x) - S_t \leq c_t^N(x) - \overline{S}_t$ is thus valid for any x. Inserting the value $x = CK_t$ and replacing $\overline{S}_t$ by its definition, the condition $\tilde{c}_t^N \left(CK_t \right) \leq c_t^R$ holds. As we have already shown that $\tilde{c}_t^N \left(CK_t + \alpha_i K_t + \sum_{\substack{j=1 \\ j \neq i}}^{n} \delta'_j \alpha_j K_t \right) < \tilde{c}_t^N \left(CK_t \right)$, these last two conditions together indicate that this player would obtain a strictly lower LCOE by unilaterally deviating from the strategy vector δ' which obviously contradicts the assumption of δ' being a NE. Q.E.D.

From this proposition, two interesting points deserve to be highlighted. First, $\overline{S}_t > \underline{S}_t$ indicates that a more generous threshold has to be considered to obtain the desired **unique** NE. Second, this threshold depends neither on the number of players (beyond one) nor on the relative capacity they control. Hence, no matter what the industrial concentration in each year is (i.e., no matter the number of players and their relative size), this threshold is always sufficient to make generalized early CC adoption the unique NE which is the desired outcome. In contrast, the following corollary indicates that that any subsidy policy S_t in the range $\overline{S}_t > S_t \geq \underline{S}_t$ cannot guarantee the existence of a unique NE for any structure of the game to be played in year t.

Corollary – We consider a given year t such that the cumulated CC capacity decided during the previous periods is $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$. For any tax-credits yielding a levelized subsidy S_t that verifies $\underline{S}_t \leq S_t < \overline{S}_t$, there exists at least one industrial configuration (i.e., a number of players and a distribution of the capacity K_t among them) such that the uniqueness of the Nash equilibrium $\delta = (1,1,...,1)$ is not verified.

<u>Proof:</u> We assume that a subsidy S_t that verifies $\underline{S}_t \leq S_t < \overline{S}_t$ is implemented. As $\underline{S}_t \leq S_t$, the strategy vector $\delta = (1,1,...,1)$ is a NE. By construction, the condition $\underline{S}_t \leq S_t < \overline{S}_t$ indicates that $c_t^N \left(CK_t + K_t \right) \leq S_t + c_t^R < c_t^N \left(CK_t \right)$ is verified. As the function c_t^N that gives the LCOE in case of early CC adoption is both continuous and strictly decreasing over the interval $\left[CK_t, CK_t + K_t \right]$, this function can be inverted and we let $c_t^{N,-1}$ denote that inverse function. We let $\alpha^* := \frac{c_t^{N,-1}\left(c_t^R + S_t \right) - CK_t}{K_t}$. As $c_t^N \left(CK_t + K_t \right) \leq S_t + c_t^R < c_t^N \left(CK_t \right)$ and

$c_t^{N,-1}$ *is strictly decreasing, this parameter verifies* $1 \geq \alpha^* > 0$. *We consider an* n^**-player game where* n^* *verifies the condition* $n^* > \frac{1}{\alpha^*}$ *and each player controls an identical share of the capacity* K_t. *Now, we consider the strategy vector* $\delta = (0,...,0)$, *whereby each player delays the adoption of CC capabilities. By deviating from that vector, a player would incur the subsidized LCOE* $\tilde{c}_t^N\left(CK_t + \frac{1}{n^*}K_t\right)$. *As* $\alpha^* > \frac{1}{n^*}$, *the condition* $\tilde{c}_t^N\left(CK_t + \alpha^* K_t\right) < \tilde{c}_t^N\left(CK_t + \frac{1}{n^*}K_t\right)$ *is verified. Replacing* α^* *by its value, we have* $\tilde{c}_t^N\left(CK_t + \alpha^* K_t\right) = c_t^R$ *and thus the condition* $c_t^R < \tilde{c}_t^N\left(CK_t + \frac{1}{n^*}K_t\right)$ *is verified which indicates that, for a player, it does not pay to deviate from the strategy vector* $\delta = (0,...,0)$. *As players are symmetric, this condition indicates that* $\delta = (0,...,0)$ *is also a N.E.*

Q.E.D.

Appendix C – A robust schedule of ITC and PTC that is immune to strategic gaming considerations

This Appendix details the assumptions and results commented in Section 2.

C.1 Assumptions and methodology

We follow the methodology in Appendix A.2 except that the tax credits are now calibrated so as to provide a levelized subsidy that is at least as large as the threshold level mentioned in the Proposition in Section 2. These tax credits thus prevent the existence of Nash equilibriums where some emitters could rationally prefer to delay CC adoption.

The simulation are successively conducted using: (i) the original projected capacity deployment scenario used in Comello and Reichelstein (2014), and (ii) the projected capacity deployments retained in Appendix A (Table A.1).

C.2 Results

In Table C.1 (respectively C.2) , we detail the "Accelerated Carbon Capture Deployment" (ACCD) tax credits obtained in the original (respectively robust) scenario when the incentives are derived from the levelized subsidy discussed in the Proposition in Section 2.[3]

Table C.1. The ACCD tax credits needed to obtain a unique NE (Original Scenario)

Year	Total Cumulative Capacity Additions decided during the previous years $\sum_{\tau<t} K_\tau$ [MW]	Fiscal Depreciation Schedule	Schedule of Investment Tax Credits	Schedule of Production Tax Credits [¢/kWh]
2017	885	MACRS	22.6%	1.84
2018	2,020	MACRS	21.1%	1.84
2019	2,370	MACRS	19.3%	1.84
2020	3,260	MACRS	12.2%	1.32
2021	4,222	MACRS	10.2%	1.32
2022	4,494	MACRS	10.2%	1.32
2023	4,943	MACRS	10.2%	1.32
2024	10,293	150% DB	10.2%	0.86
2025	12,682	150% DB	5.9%	0.82
2026	18,589	150% DB	1.1%	0.49
2027	22,896	150% DB	0.0%	0.15

Note: MACRS indicates that all capital expenditures will be eligible for the five-year accelerated depreciation schedule according to MACRS; 150% DB indicates that all capital expenditures will be subject to the current 150% balance, 20-year depreciation schedule.

[3] These results have been generated using adapted versions of the original NGCC+CC Calculator respectively named "NGCC+CC Cost Calculator_Section 2_Original.xlsx" "NGCC+CC Cost Calculator_Section 2_Robust.xlsx" that can be downloaded from Olivier Massol's webpage: https://sites.google.com/site/oliviermassolshomepage

Table C.2. The ACCD tax credits needed to obtain a unique NE (Robust Scenario)

Year	Total Cumulative Capacity Additions decided during the previous years $\sum_{\tau<t} K_\tau$ [MW]	Fiscal Depreciation Schedule	Schedule of Investment Tax Credits	Schedule of Production Tax Credits [¢/kWh]
2017	130	MACRS	22.4%	2.78
2018	130	MACRS	20.9%	2.78
2019	130	MACRS	19.1%	2.78
2020	820	MACRS	17.4%	2.78
2021	1,252	MACRS	15.2%	2.78
2022	1,524	MACRS	13.1%	2.78
2023	1,974	MACRS	11.2%	2.78
2024	7,324	150% DB	11.2%	1.11
2025	9,712	150% DB	6.7%	1.05
2026	15,619	150% DB	1.4%	0.62
2027	19,926	150% DB	0.0%	0.00

Note: MACRS indicates that all capital expenditures will be eligible for the five-year accelerated depreciation schedule according to MACRS; 150% DB indicates that all capital expenditures will be subject to the current 150% balance, 20-year depreciation schedule.

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