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

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This note details two comments on a recent policy proposal in Comello and Reichelstein (2014) aimed at favouring the early adoption of Carbon Capture (CC) technology in the next generation of thermal-based power plants to be installed in the United States.

Introduction

The prohibitively high cost of 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 brief 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 two authors must be praised for having made their data and spreadsheet model readily available to readers.

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 our evaluations confirm that this robust version is almost as attractive as the initial version:[2]

- 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.[3]

- 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.[4] This robust schedule of incentives thus represents a cost-effective solution for achieving a large scale deployment of this innovative technology.

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

[INSERT FIGURE 1 ABOUT HERE]

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.

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

Our discussion is structured as follows. A first subsection reviews the evaluation of the schedule of tax-credits used in the original article. The second subsection focuses on CC adoption in a given year by several players and proves that the incentives offered that year may not be sufficient to rule out the possible occurrence of a coordination game with multiple equilibria. As uniqueness is not achieved, these players may select an equilibrium where some emitters rationally prefer to delay CC adoption. As that phenomenon may jeopardize the desired policy outcomes, the third subsection identifies an appropriately augmented minimum level of incentives that is sufficient to overcome that issue. The last subsection reports the numerical results obtained using the associated ITC and PTC schedules. For the sake of brevity, all the formal proofs are provided in a Supporting Document.

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

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 installed during that year; and CK_t denote the state variable that gives the cumulated CC capacity already installed during the preceding years.[5]

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,[6] and $c_t^N(x)$ be the strictly decreasing function that gives the LCOE if that plants adopts CC immediately given x, the cumulated CC in operation at that date.[7]

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.

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 t so that the cumulated CC capacity available at the beginning of the next year is $CK_{t+1} = CK_t + K_t$. The tax-credits are

[5] Hence, CK_t is the sum of the capacities of all the CC plants that are already in operations when year t begins.

[6] 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.

[7] As discussed in the original paper, this LCOE figure takes into consideration a 10% first-of-a-kind premium if the cumulated capacity x is lower than the first 3 GW.

calibrated so that S_t, the levelized subsidy implemented in year t, verifies $S_t \geq \underline{S}_t$, where $\underline{S}_t$ is the threshold level:

$$\underline{S}_t := c_t^N \left(CK_t + K_t \right) - c_t^R , \tag{1}$$

The authors underline that, by construction, the tax-credits prevent possible 'deviation' from what they name an 'equilibrium path' of early CC adoption. Indeed, if one models CC adoption as a one-shot game involving 11 players (one for each year) where each player faces a binary choice with respect to early CC adoption for the entire capacity K_t, the proposed subsidy makes 'early adoption' the best response of every player when the other players also jointly decide 'early adoption'. In this game, the proposed schedule of tax-credits thus makes the decision vector stating 'early adoption' for every player a pure strategy Nash Equilibrium (NE).

B – Is that proposed subsidy sufficient?

In reality, the problem at hand involves a sequence of annual decisions and the cumulated impact of installed CC capacity on future LCOE figures generates a 'path dependency' to past CC adoption decisions. 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 the plants to be installed that year.

To address this issue, one has to examine the strategic interactions among the plants to be installed in a given year. To clarify the presentation, we consider a simplified case and assume that two identical plants of size $K_t/2$ are installed in year t. These plants are controlled by two independent players labeled '1' and '2' and we posit that each player faces a binary choice with respect to the immediate installation of CC capabilities. We also assume that early CC adoption has already been decided by all predecessors so that the cumulated CC capacity available at the beginning of the year is $CK_t = CK_{2017} + \sum_{\tau=2017}^{t-1} K_\tau$.

<u>The 'unsubsidized' game</u>

The objective of each player is to <u>minimize</u> its LCOE. Absent any tax-credits, their strategic interactions can be summarized with the 'unsubsidized' normal form game in Table 1.

Table 1. The 'unsubsidized' normal form game

[INSERT TABLE 1 HERE]

Following the authors, we posit that it pays to delay CC adoption when the rival adopts the CC technology early:

$$c_t^R < c_t^N\left(CK_t + K_t\right). \tag{2}$$

As c_t^N is assumed to be a strictly decreasing function, it also pays to delay CC adoption when the rival does not early adopt the capture technology.[8] Hence, the condition (2) indicates that 'late adoption' is a strictly dominant strategy for a player and therefore the pure strategy where both players decide 'late adoption' is the unique NE. Hence, absent any tax-credits, the two players rationally prefer to delay CC adoption.

Emergence of a coordination game

We now examine the case where tax-credits are implemented and consider the levelized subsidy level, S_t. For a player that early adopts CC capabilities, the payoff is now given by the subsidized LCOE. The 'subsidized' normal form game is thus derived from the 'unsubsidized' one by using the subsidized LCOE function $\tilde{c}_t^N$ in lieu of the unsubsidized one. Two results can be highlighted for the 'subsidized' normal form game.

Finding 1 – For any levelized subsidy that verifies $S_t \geq \underline{S}_t$, the strategy vector stating 'early adoption' for each player is a NE of the subsidized game.

Finding 2 – Implementing a levelized subsidy S_t that verifies $S_t \geq \underline{S}_t$ may not be large enough for the strategy ('early adoption', 'early adoption') to be the unique NE. In particular, a subsidy level $S_t = \underline{S}_t$ is such that ('late adoption', 'late adoption') remains a 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.

However, the existence of a NE other than the one that provides early CC adoption at level K_t in year t is a source of concern. The following finding proves that a lower-than-expected level of CC adoption in year t may undermine the ability of the proposed schedule of levelized subsidies to also achieve the early adoption of CC capabilities in subsequent years.

[8] Because $c_t^R < c_t^N\left(CK_t + K_t\right) < c_t^N\left(CK_t + \frac{K_t}{2}\right)$.

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 solely verifies the condition $S_{t+1} \geq \underline{S}_{t+1}$ can be too small to make 'early adoption' of CC capabilities the best response of an investor in year $t+1$.

C – A remedy

Because of this possible snowball effect, 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. As there can be between-year variations in the number of players and in the sizes of their plants, we believe that it is preferable to opt for a threshold level that is large enough to be independent from these considerations. The following proposition offers a sufficient condition for generalized CC adoption to occur.

Proposition – In each year t, any tax-credits yielding a levelized subsidy S_t that verifies $S_t \geq \hat{S}_t$, with $\hat{S}_t := c_t^N\left(CK_t\right) - c_t^R$ where $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_t$ is the cumulated CC capacity available at the beginning of year t, systematically induces the installation of a CC capacity K_t.

D – Application

This subsection reports the results obtained using the minimum threshold above. The numerical evaluations have been conducted assuming the robust capacity deployment scenario discussed in Section 1.[9]

Compared to the values in the original article, our evaluations indicate that the magnitude of the ITC levels remains similar; however, substantially augmented PTC are needed (cf., Figure 2).

Figure 2. The tax credit schedule needed to obtain a unique NE

[INSERT FIGURE 2 ABOUT HERE]

These new levels generate a substantial increase in the cumulative (undiscounted) foregone tax revenue to the U.S. Treasury: about $14.1 billion. This is a 110% increase over the figure obtained in the original article. Nevertheless, we believe that this cost figure remains tolerable for such an ambitious policy, especially one that would now be rendered robust to both foreign adverse events and domestic gaming issues.

[9] 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.

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 initially proposed 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, a modified version of the policy has been proposed using the detailed cost structure developed in Comello and Reichelstein (2014). Though higher incentive levels have been obtained, our findings confirm that the cost of the proposed 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.

Acknowledgements

The views expressed here and any remaining errors are our sole responsibility.

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APPENDIX

Cf. the companion document.

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

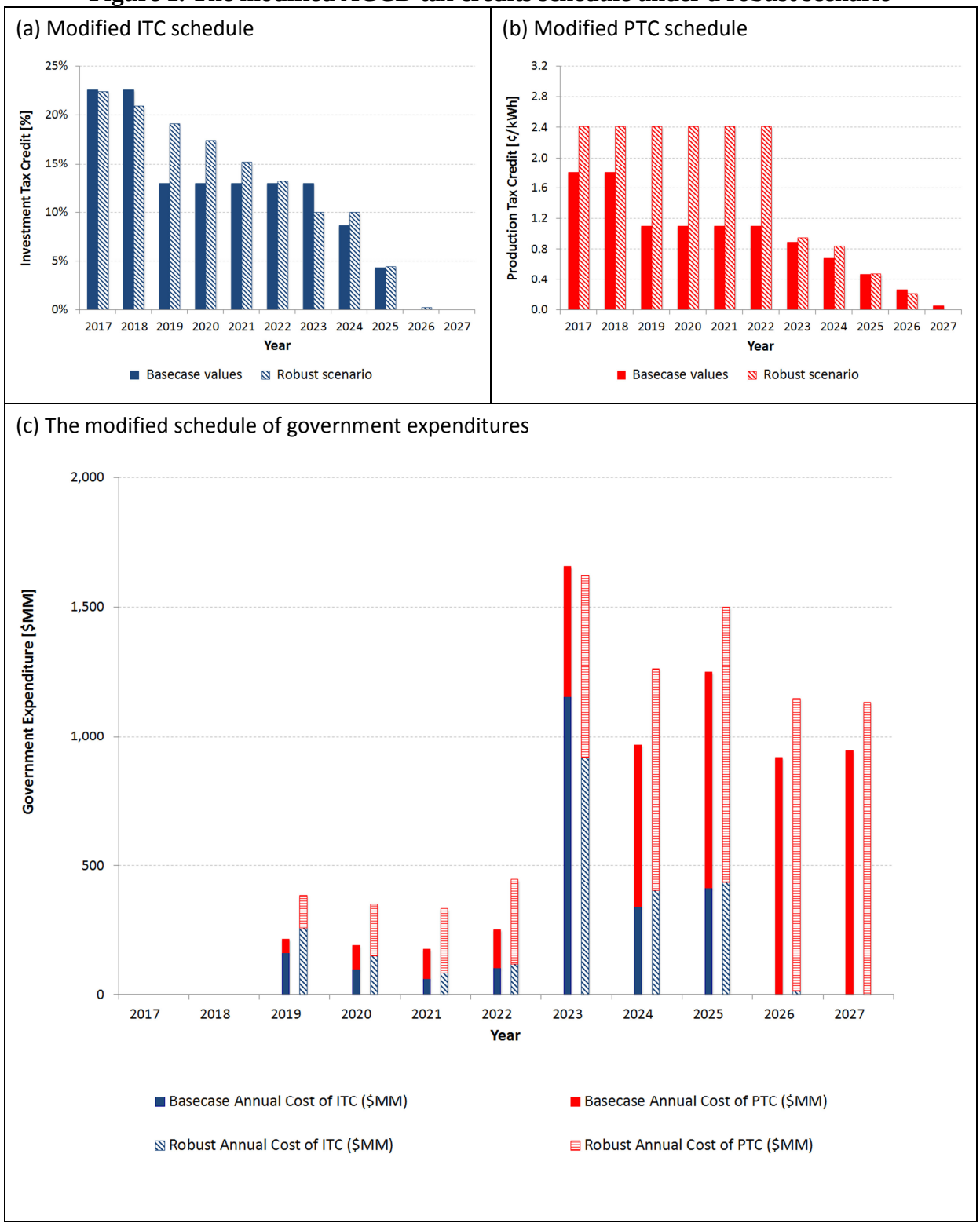
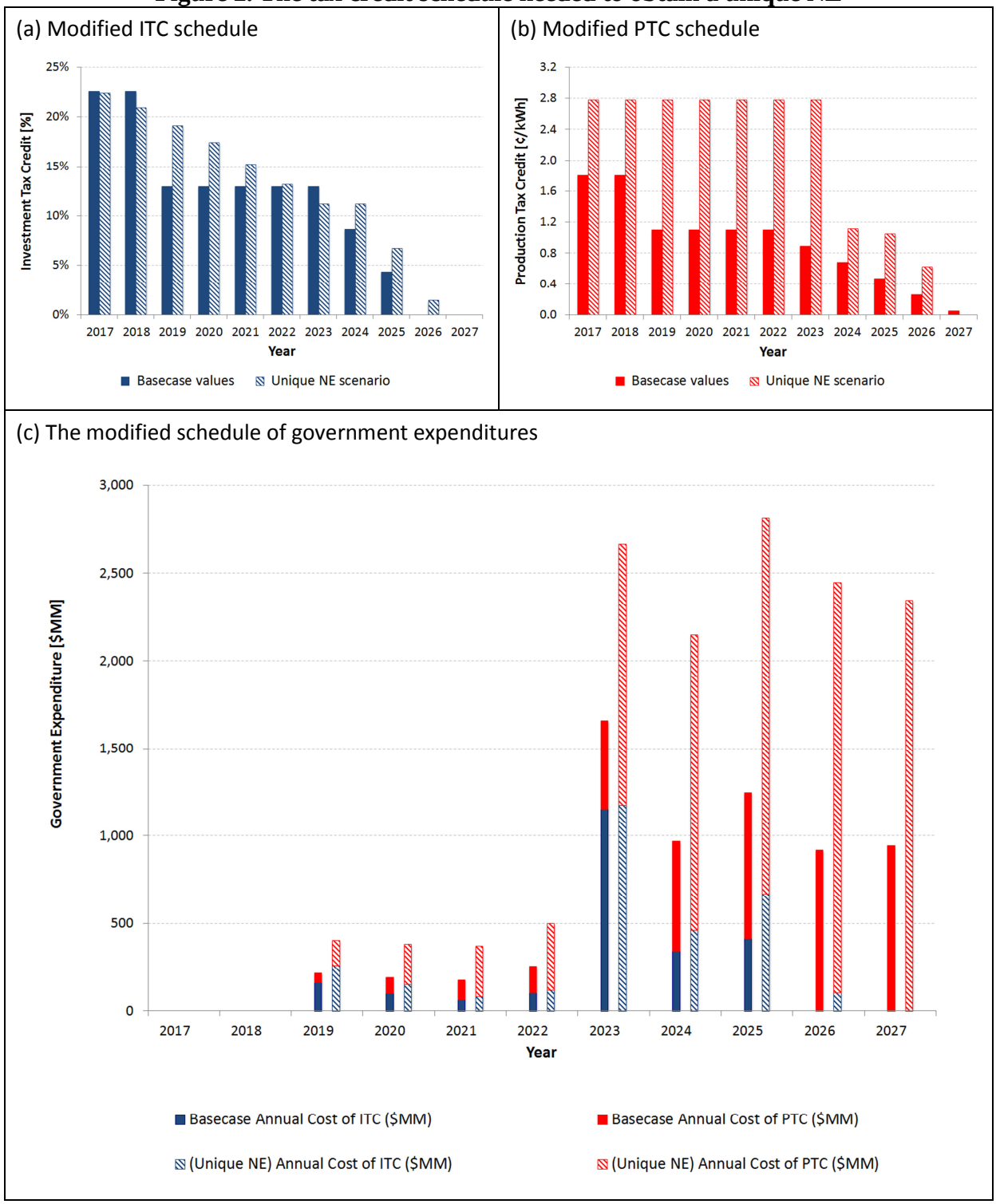


Table 1. The 'unsubsidized' normal form game

		Player 2	
		Late adoption	Early adoption
Player 1	Late adoption	$c_t^R \; ; \; c_t^R$	$c_t^R \; ; \; c_t^N \left(CK_t + \frac{K_t}{2} \right)$
	Early adoption	$c_t^N \left(CK_t + \frac{K_t}{2} \right) \; ; \; c_t^R$	$c_t^N \left(CK_t + K_t \right) \; ; \; c_t^N \left(CK_t + K_t \right)$

Note: In this paper, the objective of each player is to minimize its LCOE.

Figure 2. The tax credit schedule needed to obtain a unique NE



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.

- Appendix A (respectively Appendix C) clarifies the assumptions and methodology used to generate the numerical results commented in Section 1 (respectively Section 2) of the paper.

- Appendix B presents the mathematical proofs of the Finding 1, 2 and 3 and the Proposition stated in Section 2 of the 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. These results have been generated using an adapted version of the original NGCC+CC Calculator.[3]

[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.

[3] This modified spreadsheet model named "NGCC+CC Cost Calculator_Section 1.xlsx" can be downloaded from Olivier Massol's webpage: https://sites.google.com/site/oliviermassolshomepage/working-papers

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 – For any levelized subsidy that verifies $S_t \geq \underline{S}_t$, the strategy vector stating 'early adoption' for each player is a Nash equilibrium of the subsidized game.

Proof: Suppose both players decide 'early adoption'. Each player incurs the subsidized LCOE: $\tilde{c}_t^N\left(CK_t + K_t\right) = c_t^N\left(CK_t + K_t\right) - S_t$. *As* $S_t \geq \underline{S}_t$, *the condition* $\tilde{c}_t^N\left(CK_t + K_t\right) \leq c_t^R$ *is* de facto *verified which indicates that 'early adoption' is the best response of a player whenever its rival also picks that strategy.* *Q.E.D.*

Finding 2 – Implementing a levelized subsidy S_t that verifies $S_t \geq \underline{S}_t$ may not be large enough for the strategy ('early adoption', 'early adoption') to be the unique Nash equilibrium. In particular, a subsidy level $S_t = \underline{S}_t$ is such that ('late adoption', 'late adoption') remains a Nash equilibrium.

Proof: We have to check the conditions for the vector ('late adoption', 'late adoption') to no longer be a Nash equilibrium. We examine the best response of a player when the rival decides 'late adoption'. The condition for that player to systematically prefer 'early adoption' when the rival decides 'late adoption' is $\tilde{c}_t^N\left(CK_t + \frac{K_t}{2}\right) < c_t^R$ *which calls for a levelized*

subsidy that verifies the condition: $S_t > \overline{S}_t$ *where* $\overline{S}_t := c_t^N\left(CK_t + \frac{K_t}{2}\right) - c_t^R$. *As* c_t^N *is a strictly decreasing function, the threshold* $\overline{S}_t$ *verifies* $\overline{S}_t > \underline{S}_t$. *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 solely verifies the condition $S_{t+1} \geq \underline{S}_{t+1}$ can be too small to make 'early adoption' of CC capabilities the best response of an investor in year $t+1$.

Proof: Because of non-adoption, we assume that the CC capacity constructed in year t *attains a level* k_t *with* $k_t < K_t$. *If the levelized subsidy scheduled during the next year is set such that* $S_{t+1} = \underline{S}_{t+1}$, *the subsidized LCOE obtained in case of adoption verifies* $\tilde{c}_{t+1}^N(CK_t + k_t + k_{t+1}) > c_{t+1}^R$ *for any level of CC adoption* $k_{t+1} \in [0, K_{t+1}]$ *in year* $t+1$ *(because* c_{t+1}^N *is a strictly decreasing function).* *Q.E.D.*

Proposition – In each year t, any tax credits yielding a levelized subsidy S_t that verifies $S_t \geq \hat{S}_t$, with $\hat{S}_t := c_t^N(CK_t) - c_t^R$ where $CK_t := CK_{2017} + \sum_{\tau=2017}^{t-1} K_t$ is the cumulated CC capacity available at the beginning of year t, systematically induces the installation of a CC capacity K_t.

Proof: We assume that a player has to build a unique power plant of capacity $x_t \in [0, K_t]$ *in year* t *and let* $\tilde{x}_t \in [0, K_t - x_t]$ *be the aggregate amount of CC capacities decided by its rivals. If the levelized subsidy* S_t *is such that* $S_t \geq \hat{S}_t$, *the LCOE obtained in case of early CC adoption systematically verifies* $\tilde{c}_t^N(CK_t + x_t + \tilde{x}_t) \leq c_t^N(CK_t + x_t + \tilde{x}_t) - c_t^N(CK_t) + c_t^R$. *As* c_t^N *is a decreasing function and* $CK_t + x_t + \tilde{x}_t \geq CK_t$, *we have* $\tilde{c}_t^N(CK_t + x_t + \tilde{x}_t) \leq c_t^R$ *for any* $\tilde{x}_t$ *in* $[0, K_t - x_t]$ *which indicates that this player's best response is systematically to implement CC immediately. Applying that reasoning to any other player in year t indicates that early CC adoption is a dominant strategy for that player which indicates that the generalized early adoption of CC capabilities by all the investors is the unique Nash equilibrium.* *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

The simulation is based on the projected capacity deployments retained in Appendix A (Table A.1). 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.

C.2 Results

In Table C.1, we detail the "Accelerated Carbon Capture Deployment" (ACCD) tax credits obtained in the robust scenario when the incentives are derived from the levelized subsidy discussed in the Proposition in Section 2. These results have been generated using an adapted version of the original NGCC+CC Calculator.[4]

Table C.A. 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%	2.78
2018	MACRS	20.9%	2.78
2019	MACRS	19.1%	2.78
2020	MACRS	17.4%	2.78
2021	MACRS	15.2%	2.78
2022	MACRS	13.1%	2.78
2023	MACRS	11.2%	2.78
2024	150% DB	11.2%	1.11
2025	150% DB	6.7%	1.05
2026	150% DB	1.4%	0.62
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.

[4] This modified spreadsheet model named "NGCC+CC Cost Calculator_Section 2.xlsx" can be downloaded from Olivier Massol's webpage: https://sites.google.com/site/oliviermassolshomepage/working-papers