On Environmental Externalities and Global Games

Heijmans, Roweno J.R.K.

DOI:
10.26116/center-lis-2115

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

On Environmental Externalities and Global Games

ROWENO HEIJMANS

TILBURG UNIVERSITY

On Environmental Externalities And Global Games

Proefschrift ter verkrijging van de graad van doctor aan Tilburg University op gezag van de rector magnificus, prof. dr. W.B.H.J. van de Donk, in het openbaar te verdedigen ten overstaan van een door het college voor promoties aangewezen commissie in de Aula van de Universiteit op donderdag 26 augustus 2021 om 16.00 uur door

Roweno Johannes Ryan King Heijmans,

geboren te 's-Hertogenbosch

Promotores:	prof. dr. E.E.C. van Damme
	prof. dr. R. Gerlagh
leden promotiecommissie:	prof. dr. S. Ambec (Toulouse School of Economics)
	prof. dr. C. Fischer (Vrije Universiteit Amsterdam)
	prof. dr. G. Perino (Universität Hamburg)
	prof. dr. J.A. Smulders (Tilburg University)

ISBN 978 90 5668 656 7

"Ad tuendam naturam non sufficit ut quaedam aut nulla oeconomica subsidia praebeantur, ne congrua quidem instructio sufficit. Instrumenta sunt haec magni ponderis, sed praecipua quaestio inest in universa moralis societatis firmitudine. Si vitae mortisque naturalis ius non observatur, si artificiosa efficitur conceptio, gestatio et nativitas hominis, si humani embryones vestigationi immolantur, accidit ut communis conscientia oecologiae humanae ac simul etiam oecologiae naturae sensum amittat. Contradictorium est a novis generationibus naturae observantiam postulare, cum institutio legesque suum ipsarum cultum non adiuvant. Liber naturae unus est et indivisibilis, tam ex parte naturae quam ex parte vitae, sexualitatis, matrimonii, familiae, relationum socialium, denique humanae integraeque progressionis. Officia nostra erga rerum naturam cum nostris muneribus nectuntur quae personam respiciunt, quae per se ipsa consideratur et cum aliis relata. Non licet alia exigere et alia conculcare. Haec gravis est antinomia mentis hodiernique moris quae personam deprimit, naturam turbat ac damna societati affert."

BENEDICTUS XVI, CARITAS IN VERITATE

Voorwoord

U leest op dit moment een proefschrift. Of beter gezegd, het voorwoord tot een proefschrift. De ervaring leert dan menig lezer niet veel verder komt dan deze eerste bladzijden. Dat neem ik u niet kwalijk.

Een proefschrift is het bewijsstuk van iemands wetenschapsbeoefening, een gildeproef voor academici. Daarmee wil ik niet zeggen dat ik mijzelf een volledig bekwaam en autonoom wetenschapper acht, noch dat ik mij inbeeld een absoluut volleerd econoom te zijn. Ik denk dat men op het gebied van de wetenschap niet snel is uitgeleerd. Veeleer stel ik me voor dat dit proefschrift de laatste van mijn eerste schreden als wetenschapper aanduidt. In die zin is de vergelijking met een strikdiploma wellicht gepaster.

Nu is het algemeen bekend dat men bij de eerste stapjes bij de hand genomen dient te worden, wat zeker voor ondetgetekende geldt daar ik van nature buitengewoon onhandig ben. In het onderhavige geval werden de helpende handen uitgestoken door Eric en Reyer. Zij hebben mij de afgelopen jaren ondersteund en vooruit geholpen met als uitkomst dit boekwerk. Ik ben hun daarvoor zeer erkentelijk.

Overigens wordt mijn dankbaarheid jegens Reyer danig op de proef gesteld nu ik om dit voorwoord te schrijven terugdenk aan onze vele gedeelde reizen en avonturen.[1] Wist u bijvoorbeeld dat hij mij in Toulouse min of meer te vondeling heeft achtergelaten in de taxi van een chauffeur met wie hij bijna slaande ruzie had gemaakt? “Blijf zitten!” riep hij mij boven het gekerm van de woedende man toe. “Zolang jij in de auto zit gaat hij er niet vandoor met onze koffers.” Dat laatste bleek waar te zijn, ofschoon mij dit volstrekt niet evident leek met het oog op de boze man.

Ten slotte richt ik het woord tot mijn grootmoeder. Zij kan deze woorden niet meer lezen maar wist zonder enige twijfel dat ik ze zou schrijven. Minder dan twee maanden voor de verdediging van dit proefschrift overleed zij. Het laatste jaar van haar leven werd getekend door ziekte, alhoewel de verwachting was dat zij mijn promotie zou kunnen bijwonen. Dat laatste is niet iets wat ik zomaar geëxtrapoleerd heb uit meer algemene prognoses van haar artsen. Ik denk dat elke arts die zij in het afgelopen

[1]Deze door “verzwarende omstandigheden” verminderde dankbaarheid is een grapje. De te noemen anecdote is echter waargebeurd.

jaar gesproken heeft door oma eerder op de hoogte werd gebracht van het feit dat zij een kleinzoon had die aan het promoveren was dan van haar ziekteverschijnselen. Het was haar diepgekosterde verlangen mijn promotie bij te kunnen wonen.

Promoveren is niet altijd leuk of gemakkelijk. Dikwijls heb ik met afschuw op mijn beslissing om te gaan doctoreren teruggekeken. Veel werk is vereist en vaak is de oogst gering. Vertwijfeling en mistroostigheid markeren de weg. Telkens opnieuw wist oma's trots mij door zulke momenten van neerslachtigheid en weerzin te trekken. In die zin is dit proefschrift even zeer haar verdienste als de mijne. Vervuld van dankbaarheid voor wat zij voor mij betekend heeft en als teken van de liefde waarin ik haar gedachtenis koester wil ik dit proefschrift aan haar opdragen. *Requiescat in pace*.

's-Hertogenbosch, 20 juli 2021

Contents

CHAPTER 1

Regulating Stock Externalities

1.1 Introduction

Stock externalities are the unintended byproduct of cumulative economic activity in a market over the course of time. To a planner burdened with the control of this market, the question arises whether traditional tax or quota instruments could – or indeed should – be adjusted to the dynamic properties intrinsic to the stock externality and, if so, which instrument performs best. This paper studies these questions for environments with asymmetric information about market fundamentals.

The issue of instrument choice touches upon an influential literature that originates with Weitzman [140]. Papers in this tradition usually take an exogenously given set of policy instruments and assess their relative merits [*c.f.* 45, 71, 75, 109, 118, 128, 142, 145]. On top of these comparisons, this literature also proposes policy refinements by formulating intuitive policies that are optimized over their exogenous set of parameters. In this spirit, Kling and Rubin [89], Newell et al. [117], and Pizer and Prest [128] allow the planner to depreciate or top up banked – unused and saved for future use – allowances. Similarly, Yates and Cronshaw [144] consider banking with a discount rate for allowances (a kind of intertemporal trading ratio à la [76]). Newell et al. [117] and Lintunen and Kuusela [101] discuss adjusting quota in response to the quantity of outstanding allowances. Finally, Karp and Traeger [85, 86] study a cap on emissions that changes in response to aggregate private information inferred from price signals.

While we too propose and compare new instruments, ours is not a typical prices vs. quantities exercise. Instead of formulating intuitive policies based on some combination of existing policies, we *derive* them from primitives of the problem like market fundamentals and the externality under investigation. Rather than maximize welfare over a policy's exogenously given parameters, we maximize over policies.

Our approach means that the planner considers key characteristics of the externality carefully. For example, as discussed in [70], when regulating a stock externality with a cap-and-trade program the planner can afford to be less strict on compliance in any given period as long as overall compliance is guaranteed. The planner can be lenient in this way, but why stop there? At least in theory it is possible that further improvements of static policy instruments exist. The driving force behind any such improvement is the fact that observed outcomes in the market provide valuable information [i.e. signals, see 68] to the planner, who, in response, can adapt future policies. In this spirit, [128] develop a dynamically adjusted quantity instrument while [71] extends static taxes over time.[1] The basic idea of these novel instruments is the same: a well-devised instrument allows the planner to extract private information from the market and uses this information to make future regulation more efficient. If done well, such policy updating may be very efficient.

Yet while a dynamic framework creates opportunities for the planner to learn and update policies accordingly, it also breeds problems not encountered in static environments. The distinction between *stock* and *flow* externalities cuts to the core of these. At the risk of oversimplification, a flow externality is the byproduct of economic activity at a given point in time. A stock externality, in comparison, is the consequence of economic activity *over the course of time*. The difference matters. For stock externalities that we consider, past activity does affect the marginal externality of today's business.

What we do can now be summarized in three simple steps: (1) we build a model with asymmetric information about market fundamentals where productive activity causes a pure stock externality, (2) we show that the planner can construct instruments that drain *all* private information from the market apart from information that is only revealed through the market at the end of the last period, and (3) we derive pure price and quantity instruments that use this private information and implement the best achievable welfare levels very generally. The second step suggests a regulatory framework can approach the first-best by decreasing its regulatory time-windows. Indeed, we describe and order instruments with respect to convergence to first-best. Note that our last step is fundamentally constructive. We start from optimal social welfare and copy its conditions so that the market optimally adjusts production to changing market fundamentals. That is, we require that profit-maximizing firms are *always* incentivized to produce optimal amounts when regulated. It turns out that such instruments can always be found and are intimately related.

We apply our framework to climate change, caused mainly by the cumulative stock of emitted CO_2 [7, 61, 91]. It is by now widely accepted that the only way to avoid severe climate change is a large-scale reduction in global CO_2 emissions. There are fundamental uncertainties inherent to the problem, though. One will be the focus of attention here: the aggregate costs of abatement. While some fear that any emission

[1] Pizer and Prest also consider policy uncertainty from which, though relevant, both Heutel and this manuscript abstract away.

reduction threatens thousands of jobs, others foresee that a reduced use of fossil fuels has no significant bearing on neither economic growth nor employment. We develop policies that optimally respond when the market learns about these uncertainties. The emphasis on abatement costs is allegorical; other types of uncertainty resolved before the closing of markets, and relevant for welfare and thus regulation could be used in their stead.

Our approach may seem comparable to both [128] and [71]. The similarities are mostly superficial. Like Pizer and Prest, we develop a dynamically updated quantity instrument. Like Heutel, we introduce a new dynamic price instrument. The crucial difference is our choice of externality. While [128] and [71] study the dynamic regulation of a flow externality, our focus is on stock externalities. This distinction is important and may even reverse the ordering of instruments.[2] Details of the externality are crucial in a dynamic framework. The implicit assumption of a flow externality in the climate context is that historic emissions of greenhouse gases do not, at all, affect the marginal damages caused by climatic consequences of emissions today. We think this assumption does not square well with the natural science of climate change [see for example 7].

In the application, our proposed policy instruments can be thought of as an advanced cap-and-trade system. The planner allows firms to freely bank and borrow allowances between periods. Under our quantity instrument, the planner adapts future injections of new allowances in response to the amount of periodic over- or under-compliance. Importantly, we do *not* propose that banked emissions allowances be apprenticed or depreciated between periods![3] This is a very subtle, but also very important difference. The argument boils down to the crucial distinction between flow and stock externalities. When climate change is modeled as a pure flow externality, an extra ton of emissions last year may, in principle, have a different effect on climate change than an extra ton of emissions this year. If there is reason to believe this is true, that is a strong argument to appreciate or depreciate banked emission allowances. Yet when climate change is modeled as a pure stock externality the marginal climate damage from an extra ton of emissions is exactly the same whether they are emitted this or any other year (because all that matters is total emissions over time). An efficient instrument therefore treats the marginal climate damage of emissions in any period as equal and should not touch banked allowances. To nonetheless make aggregate emissions responsive to market fundamentals, new injections of emission allowances can instead be adjusted. Our price instrument deviates in the last period, when it does not set a quota but fixes the emission *tax* based on previous demand for allowances. Either of our two instruments may constitute an efficient means of a

[2] As a point in case, Weitzman's 2019 surprising ordering of instruments originates in his flow externality model and is reversed, as we show, for a stock externality.

[3] Compare [144] and [132].

country or group of countries to implement emissions reductions.

1.2 Model

1.2.1 Benefits, Costs, and Welfare

Consider a two-period world (relaxed in Section 1.2.8) and a representative profit-maximizing firm producing a homogeneous good. At every time $t \in \{1, 2\}$, producing an amount $\tilde{q}_t$ of the good yields benefits $B_t(\tilde{q}_t; \theta_t)$ to the firm (we abstract away from broader social benefits of production). The parameter θ_t captures market fundamentals observed by the firms at time t but not known to the planner. We conveniently write $B'_t = \partial B_t / \partial \tilde{q}_t$ and normalize θ_t such that $\partial B_t / \partial \theta_t = 1$. We assume concave benefits $B''_t < 0$. It is common knowledge that $\mathbb{E}[\theta_t] = 0$, $\mathbb{E}[\theta_t^2] = \sigma_t^2$, and $\mathbb{E}[\theta_1 \theta_2] = \rho\sigma_1\sigma_2$. In a market with free and competitive trade of production rights, an equilibrium price will emerge, denoted $\tilde{p}_t = B'_t$. For the purposes of our study, the variance σ_t^2 provides a natural measure of uncertainty in the market.

Cumulative production imposes a cost on society in the form of a stock externality, given by $C(\tilde{q}_1 + \tilde{q}_2)$. We assume convex costs, $C' > 0, C'' > 0$. Note that our approach toward stock externalities is non-standard as we assume that costs occur at the end of the final period only [*c.f.* 60, 91, 138]; this contrasts with the more typical, and general, treatment of stock externalities in which the externality imposes a cost on society in *each* period (depending on the stock of production in that period). Thus, in the application to global warming, we assume away any costs that climate change may be causing already now and only look at future damages.

The planner's problem is to find policies such that production levels $\tilde{q}_1$ and $\tilde{q}_2$ maximize welfare:

$$W(\tilde{q}_1, \tilde{q}_2; \theta_1, \theta_2) = B_1(\tilde{q}_1; \theta_1) + B_2(\tilde{q}_2; \theta_2) - C(\tilde{q}_1 + \tilde{q}_2). \tag{1.1}$$

The timing of regulation and equilibrium follows these stages:

1. The planner chooses a policy instrument;
2. Firms observe first-period ($t = 1$) fundamentals θ_1;
3. First-period markets open and production $\tilde{q}_1$ is realized;
4. Firms observe second-period ($t = 2$) fundamentals θ_2;
5. Second-period markets open and production $\tilde{q}_2$ is realized;
6. Costs due to aggregate production $\tilde{Q} = \sum_t \tilde{q}_t$ are realized.

Note that market outcomes are public information; i.e. they are observed by the planner. With complete information on θ_t, the fully knowledgeable planner can set these quantities $\tilde{q}_1, \tilde{q}_2$ directly or else charge a price on production that will make the profit-maximizing firm produce the same quantities, and these two instruments are perfectly equivalent, see Montgomery [112]. However, this formal equivalence between instruments breaks down once we introduce an informational disparity, captured here by θ_t [140].

1.2.2 Optimal Response

We study an environment with asymmetric information *and* imperfect foresight. Because of the unpredictable element in future market conditions, the ex post first best is unattainable: it would require the planner to be aware of firms' private knowledge about market fundamentals even before firms themselves are. Instead, the best instrument a planner could aim for is one that reacts to any innovations in market fundamentals as soon as they are revealed to the firms. Since such a hypothetical instrument responds optimally to new information, we call it the Optimal Response.

In terms of our model, the Optimal Response determines the cap on emissions in any period t only after θ_t, the market fundamentals in period t, has been drawn. It sets $\tilde{q}_1$ and $\tilde{q}_2$ that implement:

$$\max_{\tilde{q}_1} \mathbb{E}_1 \max_{\tilde{q}_2} \mathbb{E}_2 W(\tilde{q}_1, \tilde{q}_2; \theta_1, \theta_2), \tag{1.2}$$

where $\mathbb{E}_t$ is shorthand for the expected value of W conditional on θ_s for all $s \leq t$. (Note that this instrument is equivalent to one where prices are chosen conditional on market fundamentals).

While the Optimal Response is a hypothetical instrument, it provides a useful benchmark for policy performance. As we shall show, a smart choice of pure price or quantity instrument allows the planner to implement the Optimal Response solution in all regulatory periods but the last. When there are many periods and each period is relatively short (see Section 1.2.8), this result is remarkably strong. Simple pure price or quantity instruments suffice to let the planner implement welfare levels almost as though there were no asymmetric information. For all but the last period, complicated and multi-dimensional hybrid instruments [1, 127, 130, 141] cannot do better than our pure price and quantity instruments.

1.2.3 Linear-Quadratic Specification

The main body of our analysis will focus on a simplified model where benefits and costs are linear-quadratic in emissions. This simplest possible case will allow us to derive our new instruments – Responsive Quotas and Endogenous Taxes – constructively and in a precise parametric form. This formulation also permits an intuitive implementation of either instrument. Section 1.3 briefly returns to the general model and is devoted to proving the existence and implementability of Responsive Quotas and Endogenous Taxes generally.

Let marginal benefits and costs in period t be of the form

$$B_t'(q_t) = p^* - \beta(\tilde{q}_t - q^*) + \theta_t, \tag{1.3}$$

$$C'(q_1 + q_2) = p^* + \gamma(\tilde{q}_1 + \tilde{q}_2 - Q^*). \tag{1.4}$$

Note that we take the *average* of production q_t for cumulative production Q. This adaption facilitates a common interpretation for marginal costs γ independent of the number of periods (see Section 1.2.8).

For convenience, we normalize our notation such that variables q_t and p_t denote deviations from the ex-ante expected optimum: $p_t \equiv \tilde{p}_t - p^*$, and similarly for $q_t \equiv \tilde{q}_t - q^*$. In a competitive market, production is so allocated that prices satisfy:

$$p_t = -\beta q_t + \theta_t, \tag{1.5}$$

which is a first-order condition for profit-maximization by firms.

For simplicity, we start with the 2-period case. We assume that fundamentals θ_t follow an AR(1) process according to:

$$\theta_2 = \alpha\theta_1 + \mu, \tag{1.6}$$

with commonly known $\alpha \in [-1, 1]$ and μ white noise, so that $\sigma_2^2 = \alpha^2\sigma_1^2 + \sigma_\mu^2$, and $\rho = \alpha\sigma_1/\sigma_2$.

1.2.4 Classic Banking and the Waste of Information

Before delving into our new instruments, we quickly revisit a standard policy for dynamic cap-and-trade systems: banking (and borrowing). Under such a policy, the planner allocates an amount of emissions allowances to the market in each period but is lenient with respect to periodic compliance, as long as aggregate compliance is safeguarded [70]. This is called banking or bankable quantities because unused allowances can be "banked" for future use. In our notation, the planner sets $Q = 0$, the ex ante expected optimal stock of emissions, while firms choose their periodic emissions levels q_t subject to the constraint that $Q = q_1 + q_2$. Since the market is still free to choose $q_1 = q_2 = 0$ but is not required to do so, a basic argument establishes right away that banking always outperforms fixed periodic quantities.

Banking contains information. The decision to use an extra emission allowance in one period at the cost of emissions in the other signals some of the market's private information to the planner. To see why, consider the following simple example. Let market fundamentals be imperfectly persistent over time, i.e. $\alpha < 1$, and assume that firms decide to bank a positive amount of allowances for use in the second period, i.e. $q_1 < 0$. The planner then learns that $\theta_1 < 0$: firms maximize expected profits, which means emissions in each period are chosen so that $p_1 = \mathbb{E}p_2$, or $\theta_1 - \beta q_1 = \alpha\theta_1 - \beta q_2$, which (for $q_2 = -q_1$) is consistent with $q_1 < 0$ if and only if $\theta_1 < 0$.

But if $\theta_1 < 0$, the initial (aggregate) allocation of $Q = 0$ allowances is too loose and the planner knows it. After the first period market has cleared, the planner who implements a pure banking policy is stuck with a known-to-be inefficient allocation, forced to disregard the valuable information that the market's banking decision has made readily available. Surely the planner can do better?

1.2.5 Responsive Quotas

We first develop our optimal pure quantity instrument. This instrument resembles the many cap-and-trade systems operative across the globe to reduce greenhouse gas emissions (including EU ETS, RGGI, UK ETS, China ETS, South-Korean ETS, California ETS), though with an important modification: new permit injections are a function of the outstanding amount of allowances banked. We call this policy Responsive Quotas.

Starting from classic cap-and-trade, we show how the planner can construct a policy that filters all private information about fundamentals from the market and, exploiting that firms maximize profits and anticipate the planner's response to any observed first-period behavior, implements the ex post efficient level of emissions in the first period. Formally, this instruments yields the following welfare maximization program:

$$\max_{q_1, q_2} \quad \mathbb{E}_1 W(q_1, q_2), \tag{1.7}$$

that is, emissions in *both* periods are determined only after market fundamentals in the first period are observed by the firms. Much different from classic banking, the total cap on emissions is endogenous to market fundamentals as revealed through banking under a Responsive Quotas regime. We may therefore define the planner's policy-response R such that the $Q = R(q_1)$, i.e. the function R translates first-period emissions q_1 into an endogenous aggregate cap on emissions Q. The problem of our planner is then to find an optimal response function R.

Since firms maximize expected profits, after observing θ_1 they will choose q_1 such that $p_1 = \mathbb{E}_1 p_2$, or $\theta_1 - \beta q_1 = \alpha\theta_1 - \beta(R(q_1) - q_1)$, which uses that firms anticipate the planners policy of setting $Q = R(q_1)$ and the AR(1) development of market fundamentals. The planner, in turn, wants to maximize welfare and therefore equates (expected) marginal benefits to marginal climate damages, given by $\gamma(q_1 + q_2) = \gamma R(q_1)$. An optimal response function R^* therefore solves:

$$\theta_1 - \beta q_1 = \alpha\theta_1 - \beta(R^*(q_1) - q_1) = \gamma R^*(q_1), \tag{1.8}$$

for all first-period fundamentals θ_1. See Section 1.3 for the existence result of an optimal response function R^* for general costs and benefits. In our linear model, the optimal response function R^* specifies a simple linear relationship:

$$Q = \delta^* q_1, \tag{1.9}$$

where δ^*, the optimal response rate, is given by:

$$\delta^* := \frac{Q}{q_1} = \frac{(1+\alpha)\beta}{(1-\alpha)\gamma + \beta}. \tag{1.10}$$

Note that the response of cumulative allowances equals the injection of allowances in the second period. Looking at (1.9), Repsonsive Quotas coincides with a standard banking and borrowing policy when $\delta^* = 0$. From (1.10), this will be the case only if marginal damages rise very sharply with emissions ($\gamma \to \infty$) or if marginal benefits are constant ($\beta = 0$). In all other cases, Responsive Quotas strictly outperforms standard banking and borrowing.

The optimal response rate is increasing in the persistence α of market fundamentals. The more fundamentals are expected to persist, the likelier it becomes that an increase in the marginal value of emissions in the first period is matched in the second. If $\alpha = -1$, fundamentals are perfectly negatively correlated, and any first-period decrease in demand offsets an equal increase in second-period demand; there is no reason to adjust the cap, $\delta^* = 0$. At the other extreme, if fundamentals are perfectly and positively correlated, a first-period decrease in demand is matched by an equal decrease in second-period demand; the adjustment of the cap doubles the observed adjustment of first period demand, $\delta^* = 2$.

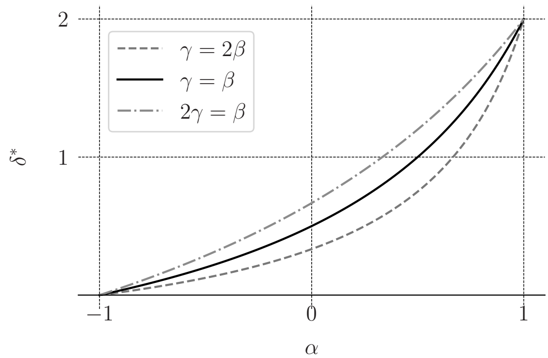

Figure 1.1 – Optimal Response Rate δ^*, for different ratios γ/β, dependent on the correlation between fundamentals α.

If we plug the optimal R^* (or δ^*) back into the planner's welfare maximization problem, we see that a Responsive Quotas policy forces profit maximizing firms to choose first-and second-period emission levels that are ex post efficient with respect to first-period market fundamentals. By exploiting rational firms' anticipation of the planner's policy updating through R^*, it is almost as though the first period is retro-actively regulated, after it has cleared. This is also evidenced by the expected welfare losses under an Responsive Quotas policy relative to the ex post social optimum, which derive solely from unforeseen innovations in second-period market fundamentals:

$$\mathbb{E}W^{OR} - \mathbb{E}W^{RQ} = \frac{1}{4}\frac{1}{\beta + \gamma}\sigma_\mu^2. \tag{1.11}$$

We conclude our discussion of Responsive Quotas with two key observations. First, depreciating or topping up privately banked allowances à la [89] and [144] will not work for a pure stock externality. The stabilization rate δ^* *cannot* be interpreted as an intertemporal trading ratio for emission allowances. An efficient policy lets firms internalize the marginal damage caused by its emissions. But for a stock externality, the marginal damage is the same in each period. Firms' decisions to bank allowances should therefore be driven exclusively by (expected) market fundamentals. An intertemporal trading ratio different from 1 distorts this tradeoff.

Second, a direct comparison of our Responsive Quotas with Pizer and Prest's (2020) optimal dynamic quantities is not necessary. Our approach has been constructive: we let the structure of our problem dictate the ideal quantity instrument. The instrument implements first-best emission levels in both periods if there are no innovations (i.e. $\mu = 0$) in market fundamentals. If Pizer and Prest's flow externality instrument were optimal for stock externalities as well, our method would have reproduced it. Since it did not, Responsive Quotas outperform Pizer and Prest's quantity instrument for regulating stock externalities (and theirs outperforms Responsive Quotas for flow externalities).

Our Responsive Quotas policy is somewhat similar to the workings of the EU's Emissions Trading System since its 2018 reform.[4] A crucial aspect of the EU ETS post-reform is that the supply of new allowances is endogenous to the amount of outstanding, or unused, allowances held by the market. When this "bank" exceeds the threshold of 833 million allowances, a pre-defined percentage of the total number of allowances in circulation is not issued but instead placed in the Market Stability Reserve (MSR); if, in any year, the MSR contains more allowances than were auctioned in the previous year, the excess is permanently canceled. Thus, the EU ETS adjusts its cumulative cap in response to emissions/banking decisions by firms. Despite this general similarity, though, there are at least two important differences between a Responsive Quotas policy and the workings of the EU ETS. First, Responsive Quotas are continuous in emissions/banking (see (1.9)) whereas the EU ETS by construction operates in a discrete way. Second, the cumulative cap can adjust both downward

[4] To be more precise, the reform was agreed upon in 2018; it will be operative as of 2021 only.

and upward under a Responsive Quotas policy; in the EU ETS, the cumulative cap can be tightened only.

1.2.6 Endogenous Taxes

Responsive Quotas is the optimal quantity instrument to regulate a pure stock externality. We can similarly devise an optimal price policy. This is the exercise undertaken here. We call our new instrument Endogenous Taxes.

If the planner taxes emissions at a rate of p_1 in the first period, then after observing θ_1 profit-maximizing firms choose q_1 so that $p_1 = \theta_1 - \beta q_1$. Since the chosen level of emissions reveals first-period market fundamentals θ_1, the planner can adjust the second-period tax according to some tax-response function $p_2 = T(q_1)$. As for Responsive Quotas, the planner's problem is to find an optimal tax-response function T^* that maximizes welfare conditional on first-period market fundamentals θ_1. In our model's language, the tax-response function T^* should implement the solution to:

$$\max_{p_1,p_2} \quad \mathbb{E}_1 W(q_1(p_1), q_2(p_2)), \tag{1.12}$$

In our linear model, the optimal tax-response function T^* is linear with slope τ^*:

$$p_2 = \tau^* q_1. \tag{1.13}$$

But, to implement the best price instrument, the first-period price must autonomously adjust to the fundamentals θ_1, so that the optimal first-order condition $p_1 = \mathbb{E}_1 p_2$ is satisfied. The regulator can achieve this feat by allocating allowances, fixing the second-period price to its optimal level based on its first-period information, and let free banking and borrowing link the markets. A recursive tax policy cannot reach this outcome, which is why we label it 'Endogenous Taxes'. Under this construction, the optimal price response becomes

$$\tau^* = \frac{(1+\alpha)\beta\gamma}{(1-\alpha)\gamma + \beta}. \tag{1.14}$$

Upon closer inspection of (1.10) and (1.14), it turns out the Responsive Quota and Endogenous Taxes instrument are fundamentally related. We observe that

$$\tau^* = \gamma \cdot \delta^*. \tag{1.15}$$

The normalized (i.e. unit-less) optimal updating rule τ^*/γ coincides with δ^*, the optimal stabilization rate for Responsive Quotas. While perhaps surprising at first, this is in fact intuitive. If first-period emissions are q_1, then the aggregate cap is adjusted to $\delta^* q_1$ under a RQ regime, and the adjustment of marginal damages is therefore $\gamma(\delta^* q_1)$. By construction, this response is efficient in expectations, so

$\Delta MB_1 = \Delta \mathbb{E}_1 MB_2 = \Delta MC = \gamma\delta^* q_1$, i.e marginal benefits in the first period equal expected marginal benefits (no innovations) in the second period, which equal marginal costs. But if $\Delta MB_2 = \gamma\delta^* q_1$ is in expectations efficient, then a *price* instrument should tax second-period emissions at a rate $p_2 = \gamma\delta^* q_1$ also. Since Endogenous Taxes is defined as $p_2 = \tau^* q_1$, see (1.13), it follows that a welfare-maximizing planner chooses $\tau^* = \delta^* \cdot \gamma$.

The expected welfare losses under an Endogenous Taxes regime derive solely from unforeseen innovations in the second period:

$$\mathbb{E}W^{OR} - \mathbb{E}W^{ET} = \frac{1}{4}\left(\frac{\gamma}{\beta}\right)^2 \frac{1}{\beta + \gamma}\sigma_\mu^2 \tag{1.16}$$

Note that our approach has been constructive: we let the fundamentals of our problem dictate the ideal price instrument. If Heutel's (2020) Bankable Prices were the optimal price instrument for stock externalities as well, our method would have told us so. Since it did not, Endogenous Taxes outperform Heutel's Bankable Prices for regulating stock externalities. Another way to see this to observe that Endogenous Taxes implements the same price in both periods for any innovation in fundamentals, and first-best emission levels in both periods if there are no innovations in market fundamentals. Bankable Prices does not preserve those two properties, which are efficient for stock externalities since marginal damages are period-independent.

1.2.7 Prices vs. Quantities

If there are no innovations in second-period market fundamentals, both Responsive Quotas and Endogenous Taxes implement the first best level of emissions in either period and neither instrument is favored over the other [112]. When second-period innovations are possible, the instruments only deviate with respect to the effect of these innovations in the second period. The relative performance of our instruments is therefore determined solely by how unforeseen second-period fundamentals affect emissions in the second period. This boils down to the classic choice problem studied by [140].

Proposition 1 (Weitzman for Stock Externalities)**.** *Endogenous Taxes outperform Responsive Quotas in terms of welfare if and only if $\beta \geq \gamma$:*

$$\mathbb{E}W^{ET} \geq \mathbb{E}W^{RQ} \iff \beta \geq \gamma. \tag{1.17}$$

For constant marginal damages, $\gamma = 0$, the first best is relatively straightforwardly implemented by setting the price to match those. When knowledge about the true marginal damages evolve over time, a generalized version of the Endogenous Taxes policy uses all information available to the market to set the market price at the expected value for marginal damages, at each point in time. Importantly, a stock externality still requires that current prices equal expected prices, which is the core property of Endogenous Taxes not upheld by other instruments in the literature.

The jury is still out whether climate damages are convex ($\gamma > 0$) or proximately linear ($\gamma = 0$) in greenhouse gas emissions.[5] In either case, however, Endogenous Taxes is favored over Responsive Quotas if the number of periods N becomes large, as we see below.

1.2.8 A Finer Grid

Increasing the number of periods to $N > 2$, we also increase the number of market operations that can be regulated, effectively using each trading opportunity as an instrument. Much like in the two-period model, this allows the planner in every period but the last to implement emission levels that are first best given that period's market fundamentals. With more and more periods, the relative effect of the final period (where asymmetric information continues to plague the planner) on welfare becomes smaller and smaller and the welfare performance of our instruments increases.

Consider a time window of unit length, $t \in [0, 1]$, divided in N periods of equal duration $\varepsilon = 1/N$, so that the n^{th} period ($n \in 1, ..., N$) covers the interval $[(n-1)\varepsilon, n\varepsilon]$. Benefits and costs are given by

$$B'_n = \theta_n - \beta q_n, \tag{1.18}$$

$$C' = \gamma Q = \frac{\gamma}{N} \sum_{n=1}^{N} q_n, \tag{1.19}$$

while demand shocks follow the AR(1) process

$$\theta_n = \alpha^{1/(N-1)} \theta_{n-1} + \mu_n \tag{1.20}$$

with $\theta_1 \sim N(0, \sigma)$ and $\mu_n \sim N(0, (1 - \alpha^{2/(N-1)})^{1/2}\sigma)$ iid so that ex-ante demand uncertainty is independent of the grid, $\forall n : \theta_n \sim N(0, \sigma/N)$, and α measures the last-period demand shock correlation to first period demand shock: $\mathbb{E}_1\theta_N = \alpha\theta_1$.

To see how well our instruments can do, consider again the Optimal Response discussed in Section 1.2.2, i.e. the hypothetical policy where the planner chooses q_t only after observing θ_t.[6] The Optimal Response turns out to provide a useful

[5] See for example [133] and [37], who argue there are strong non-linearities, versus [26], who argue that damages are at most linear.

[6] In this N-period model, the Optimal Response is defined as:

$$\max_{q_1} \mathbb{E}_1 \max_{q_2} \mathbb{E}_2 \cdots \max_{q_N} \mathbb{E}_N W(q_1, q_2, \cdots, q_N; \theta_1, \theta_2, \cdots, \theta_N).$$

benchmark for instrument performance since, as we show, the difference in welfare between either Responsive Quotas or Endogenous Taxes and the Optimal Response becomes vanishingly small if there are many periods. This reminisces the result in Roberts and Spence [130] and Weitzman [141], who show that one can approximate the environmental marginal damage curve arbitrarily closely by combining an increasing number of specific quantity and price instruments. A formal characterization of the Optimal Response is given in the Appendix.

Yet while it is somewhat intuitive that welfare losses become vanishingly small with increasingly fine grids, we establish a substantially stronger result: Endogenous Taxes approaches the Optimal Response welfare level for an increasingly fine grid of trades two orders of magnitude faster than Responsive Quota. Let $W_N^{OR} - W_N^i$ be the welfare losses under policy i compared to the Optimal Response with N regulatory periods. Our interest is primarily in the performance of our new instruments Endogenous Taxes (ET) and Responsive Quotas (RQ).

Theorem 1. *Let N denote the number of periods. For sufficiently large N, polices are strictly ordered $OR \succ ET \succ RQ$. The welfare gap between the best possible allocation OR and the policies decreases with N according to*

$$\mathbb{E}W^{OR} - \mathbb{E}W^{ET} = O(N^{-4}), \tag{1.21}$$

$$\mathbb{E}W^{OR} - \mathbb{E}W^{RQ} = O(N^{-2}). \tag{1.22}$$

That is, Endogenous Taxes approaches the Optimal Response welfare level for an increasingly fine grid of trades two orders of magnitude faster than Responsive Quota. The welfare loss associated with Standard Banking does not vanish for many periods.

1.2.9 Implementation

We discuss possible approaches to implement our instruments here.

Responsive Quotas can be implemented by means of a cap-and-trade system where new allowances are periodically injected. The planner is lenient with respect to periodic compliance, but aggregated over all regulatory periods firms must comply with their allocations. Periodic lenience can be achieved by allowing firms to bank and borrow emission allowances between periods, much like many emissions trading systems operative today do. The difference between cap-and-trade with banking and Responsive Quotas is that the number of new allowances injected in any given period becomes a function of the amount of banked allowances under a Responsive Quotas regime. Qualitatively, this implementation of Responsive Quotas comes remarkably close to the European Union's Emissions Trading System after its 2018 revision [58, 124].

Endogenous Taxes, though a pure price instrument, can be implemented by the same cap-and-trade system as Responsive Quotas, with the exception of the last period when the hard cap on emissions is abandoned and allowances are auctioned for a fixed price. The final-period auction price depends on cumulative surrendered allowances.

It may be puzzling that a pure price instrument is implemented, to a substantial extent, by a cap-and-trade system in all but the last period. We exploit one of our key results here: both Responsive Quotas and Endogenous Taxes implement Optimal Response (no asymmetric information) emissions levels in all but the final period. Hence, for all periods up to the last these instruments are essentially equivalent. The only difference arises in the last period, where our proposed implementation of an Endogenous Taxes regime indeed deviates from a pure Responsive Quotas policy by taxing emissions.

Importantly, the fact that Endogenous Taxes can be implemented by a combination of Responsive Quotas and a final-period tax does *not* mean it is a hybrid instrument. From the very definition, Endogenous Taxes is a pure price instrument, as it does not set any quantity constraints.

1.3 The General Case: Two Existence Results

In the preceding analysis, we develop our new instruments for the case of linear-quadratic costs and benefits. We did so for the ease of exposition. In this section, we briefly define the most general versions on Responsive Quotas and Endogenous Taxes. We then show that these general instruments can be implemented for any concave benefits and convex costs. To that end, we first need to give a general characterization of an instrument.

We characterize an instrument as the choice of policy variables for both periods, x_1, x_2 with $x = (x_1, x_2)$, such that they maximize expected welfare *given* an optimization program, where "given" means "for fixed points in time at which x_1 and x_2 are determined". Formally, an instrument implements the solution to:

$$\max_{x_1} \mathbb{E}_{t_1} \max_{x_2} \mathbb{E}_{t_2} W(\tilde{q}_1(x), \tilde{q}_2(x); \theta_1, \theta_2), \tag{1.23}$$

where t_1 (t_2) is the point in time at which x_1 (x_2) is decided upon.

In this characterization, the defining element of any price or quantity instrument is the timing at which its levels are set, indicated in (1.23) by the subscripts $0 \le t_1 \le t_2 \le 2$ of the expectations operators. When $t_i = 2$, the choice of policy variable x_i is decided after all information (θ_1 and θ_2) is collected and we can omit the expectations symbol. When $t_i = 1$, x_i is determined after θ_1 is observed but before θ_2 is observed, while $t_i = 0$ implies choosing x_i before any information is revealed.

With the general characterization (1.23) of an instrument in mind, we recall that our optimal pure quantity instrument Responsive Quotas implements (1.7), i.e. it fixes q_2

after q_1 has been realized. Thus we defined a response function R such that:

$$Q = R(q_1). \tag{1.24}$$

The defining characteristic of such a response function is that, by making second period quantities a function of first period emissions, it lets firms choose q_1 while knowing how this will affect q_2, their allocation in the second period. A smart choice of R therefore tries to set q_2 in such a way that firms choose both q_1 and $q_2 = R(q_1) - q_1$ optimally in light of the first-period fundamentals (θ_1). If such a R can be found, it implements the solution to (1.7). For the case of linear marginal costs and benefits, we saw in Section 1.2.5 that an optimal R^* implementing (1.7) exists. Remarkably, one can show that this result generalizes: response-function R implementing the solution to (1.7) exists for any concave benefits and convex costs.

Theorem 2. *For any concave benefits B_t and convex costs C, there exists an optimal response function R^* that implements the solution* (1.7).

Similarly to Responsive Quotas, Endogenous Taxes is defined as the instrument that implements (1.12). It fixes the emissions tax in both periods after first-period market fundamentals are realized. We defined a tax-response function T which sets prices in the second period in response to emissions in the first:

$$p_2 = T(q_1). \tag{1.25}$$

Section 1.2.6 illustrated that a policy-response function T^* implementing Endogenous Taxes can be found in a model with linear marginal benefits and costs. Theorem 3 establishes that such a T^* can be found for all concave benefits and convex costs.

Theorem 3. *For any concave benefits B_t and concave costs C, there exists an optimal response function T^* that implements the solution* (1.12).

1.4 Discussion and Conclusions

1.4.1 Contributions and Limitations

This paper makes several contributions. We extend a recently emerging literature on the choice and refinement of dynamic policy instruments [71, 128, 142] to environments where pollution causes a stock, rather than a flow, externality. Using only information on emissions readily available in the market, the policymaker can eliminate all welfare losses deriving from uncertainty and asymmetric information save for those caused by unforeseen (by both policymaker and firms) innovations in the final period. The idea of using market signals to solve the asymmetric information problem links our paper to seminal contributions by [97] and [34]. In this framework, we establish a strong case for price-based regulation when there are many opportunities to learn and update the policy: a well-designed tax scheme converges to the optimal response two orders of magnitude faster than an optimal quantity-based policy. Importantly, these results do not rely on commitment [*c.f.* 21] – although our policies operate according to pre-specified rules, the policymaker would have no incentive to deviate from them even if this were allowed.

Our analysis also has important limitations. The first is our simplified treatment of dynamic stock pollution: as in [91], [138], and [60], we assume that damages occur only at the end of the final period and ignore intermediate damages. This assumption is restrictive compared to more general treatments of stock externalities where the stock of pollution causes damages in each period [87, 118]. Another limitation is our take on market fundamentals: we assume that *if* a deviation from ex ante expected emissions occurs, then this must be caused by a shock that happened in the first period. In practice, it is perfectly possible that firms instead respond to an anticipated future shock [57] – when this happens, our policies are not optimal and emissions might increase whereas a decrease would be optimal or vice versa (this possibility is ruled out when updating the cap based on observed prices rather than emissions). A more complete theory of stock externality regulation should be robust to both types of shock. Lastly, we assume that the policymaker only uses information on emissions to update the cap or carbon price. For a model of cap-updating on the basis of price information, see [87].

More generally, a critical note pertaining to both this paper and the broader literature concerns the way it models informational frictions. Although many papers, including ours, address policy design and performance in environments with "uncertainty", still much more is assumed to be known than unknown. In most models, when observables such as emissions deviate from planners' expectations the only possible explanation is an unexpected "shift", or shock, in the intercept of the marginal abatement cost function. While there is little doubt such uncertainty may be relevant, many other equally reasonable explanations are – often implicitly – ruled out. Why would a policymaker, though unaware of the intercept, be perfectly informed about the *slopes* of firms' marginal abatement costs [as an exception to this rule, 75, study slope uncertainty]? Why would the persistence and variance of abatement cost shocks be known with full certainty? These and related questions motivate the study of policy design under deep or fundamental uncertainties. The development of such a theory is left for future work.

1.4.2 Policy Implications

Despite its limitations, our model generates several insights for climate policy. First, an efficient policy (whether a cap on emissions or a carbon tax) adjusts in response to learning over time. This conclusion supports a key message of the recent literature on dynamic cap and trade schemes [87, 128]. The reason is quite intuitive: an optimal policy maximizes the total benefits due to emissions minus the costs of climate change. When over time the planner learns new information about benefits, it will likely turn out that the initial cap or tax was set suboptimally; adjustments are then called for.

Second, the exact nature of an externality is fundamental to policy design. The ordering of identical instruments may (partially) reverse between stock and flow externalities (*c.f.* our results versus [142]). Relatedly, whether or not a cap on emissions can, in an efficient policy, be endogenized through an “interest rate” on banked allowances [89, 144] depends crucially on the kind of externality considered. This observation illustrates that policymakers should carefully consider the dynamics of the concrete problem at hand before taking up policies suggested by the literature; policies that works just fine for flow externalities may be a bad choice when regulating stock externalities (and vice versa).

Third, when there are many periods, learning is fast, and the policymaker uses information one quantities (e.g. emissions) to update its policy, a tax performs far better than a cap and trade scheme. Dynamically updated taxes may be a highly efficient policy solution to climate change and other stock externalities.

1.4.3 Concluding Remarks

We study the optimal regulation of pure stock externalities in environments when firms possess private information and the future is partly unpredictable. In its most general form, we define regulation as the implementation of a welfare maximization problem. This constructive approach yields two policies, Responsive Quotas and Endogenous Taxes, each of which always exists and is strictly welfare superior among all pure quantity and price instruments, respectively. Both instruments implement welfare levels that converge (faster than standard policies including recursive quota and recursive taxes) to the Optimal Response, the hypothetical level of welfare attained when a planner is informed about market fundamentals at the same time firms are. Our instruments therefore allow the planner to regulate the market almost as though there were no asymmetric information. This means our new instruments could yield substantial gains in social welfare compared to currently existing policies, for example in the mitigation of CO_2 emissions. With regard to the latter application, we suggest fairly simple ways in which our instruments can be implemented as an adaptation of existing cap-and-trade policies. Given the abundance of cap-and-trade programs across the global – think of the European Unions Emissions Trading System (EU ETS), the Regional Greenhouse Gas Initiative, the Chinese national carbon trading scheme, the UK ETS, California’s cap-and-trade program, and South-Korea ETS – our results may provide useful guidance in the design and adaption of policies to mitigate climate change.

1.A General Model Existence of Response Functions that support Theorems 2 and 3

Proof. We only need to establish that information in q_1 and θ_1 are identical, that is, that q_1 is monotonic in θ_1. We prove this for Responsive Quotas explicitly. The same algebra can be applied to Endogenous Taxes.

Totally differentiating the condition that prices are constant in expectations (i.e. realized first-period prices are equal to expected second-period prices), we obtain:

$$B_1''dq_1 + d\theta_1 - \mathbb{E}_1 B_2''dq_2 - \mathbb{E}_1 d\theta_2 = 0. \tag{1.26}$$

Similarly, when we totally differentiate the first-order condition that prices in expectations equal marginal costs, we find:

$$B_1''dq_1 + d\theta_1 - C''(dq_1 + dq_2) = 0. \tag{1.27}$$

We can multiply (1.26) by C'' and (1.27) by $\mathbb{E}_1 B_2''$ and subtract one from the other, to obtain:

$$[B_1'' \cdot C'' - B_1'' \cdot \mathbb{E}B_2'' + C'' \cdot \mathbb{E}_1 B_2'']dq_1 + [C'' - \mathbb{E}_1 B_2'']d\theta_1 - C''\mathbb{E}_1 d\theta_2 = 0 \tag{1.28}$$

This in turn can be rewritten to yield:

$$\frac{\mathbb{E}_1 d\theta_2}{d\theta_1} = \frac{C'' - \mathbb{E}_1 B_2''}{C''} + \frac{B_1''C'' - B_1''\mathbb{E}_1 B_2'' + C''\mathbb{E}_1 B_2''}{C''}\frac{dq_1}{d\theta_1} \tag{1.29}$$

Since $B_t'' < 0$ and $C'' > 0$ by assumption, the first term on the RHS is larger than one:

$$\frac{C'' - \mathbb{E}_1 B_2''}{C''} > 1. \tag{1.30}$$

Moreover:

$$\frac{B_1''C'' - B_1''\mathbb{E}_1 B_2'' + C''\mathbb{E}_1 B_2''}{C''} < 0. \tag{1.31}$$

Clearly, then, if $\mathbb{E}_1 d\theta_2/d\theta_1 \leq 1$, it is immediate that $dq_1/d\theta_1 > 0$ and any response $q_1 + q_2$ dependent on θ_1 can be written implicitly as dependent on q_1. $\square$

1.B Linear Demand, N periods

In this section we describe in detail the allocations brought about by the various policies, and the welfare gaps. The elements of Theorem 1 are proven as part of the policy characterization.

1.B.1 One-period model for reference

It will turn out convenient, for the N-period model, to have the one-period Weitzman (1974) model at hand. In the competitive market, prices satisfy:

$$p = -\beta q + \theta. \tag{1.32}$$

The Social Optimum is characterized by:

$$p^{SO} = \frac{\gamma}{\beta+\gamma}\theta, \tag{1.33}$$
$$q^{SO} = \frac{1}{\beta+\gamma}\theta \tag{1.34}$$

When the regulator sets quota at its ex-ante optimal level $q^Q = 0$, prices given by market equilibrium (1.32), $p^Q = \theta$, and welfare losses are given by

$$\mathbb{E}W^{SO} - \mathbb{E}W^{Q} = \mathbb{E}\left[\frac{1}{2}(p^{SO}+p^{Q})(q^{SO}-q^{Q}) - \frac{1}{2}\gamma(q^{SO}+q^{Q})(q^{SO}-q^{Q})\right] \tag{1.35}$$
$$= \frac{-1}{2}\frac{1}{\beta+\gamma}\sigma^2 \tag{1.36}$$

When the regulator sets the tax at its ex-ante optimal level $p^P = 0$ quantity follows, $q^P = \frac{\theta}{\beta}$. Welfare losses are given by

$$\mathbb{E}W^{SO} - \mathbb{E}W^{P} = \mathbb{E}\left[\frac{1}{2}(p^{SO}+p^{P})(q^{SO}-q^{P}) - \frac{1}{2}\gamma(q^{SO}+q^{P})(q^{SO}-q^{P})\right] \tag{1.37}$$
$$= \frac{-1}{2}\frac{\gamma^2}{\beta^2(\beta+\gamma)}\sigma^2 \tag{1.38}$$

To check consistency, note that we reproduced the result by Weitzman [140] that $\mathbb{E}W^Q > \mathbb{E}W^P$ iff $\beta < \gamma$.

1.B.2 Banking with fixed cumulative supply

Cumulative Quota solves the set of equations $\mathbb{E}_m B'_{m+1} = \mathbb{E}_m B'_{m+2} = ... = \mathbb{E}_m B'_N$, with

$$\mathbb{E}_m B'_n = \alpha^{\frac{n-m}{N-1}}\theta_m - \beta \mathbb{E}_m q_n \tag{1.39}$$

We sum all equations, divide by N, exploit $\frac{1}{N}\sum_{n=m+1}^{N} q_n = -Q_m$, write $\mathbb{E}_m p_N$ for expected marginal benefits. Combining with the price equation (1.5), we find

$$p_m = \frac{\beta}{x_m}Q_{m-1} + \frac{A_m}{x_m}\theta_m \tag{1.40}$$

$$q_m = \frac{-1}{x_m} Q_{m-1} + \frac{1}{\beta}\left(1 - \frac{A_m}{x_m}\right)\theta_m. \tag{1.41}$$

Note that the allocation characterization for Cumulative Quota converged to Optimal Response for $\gamma \to \infty$. As CQ does not adapt cumulative production to observed demand changes, it is uniformly more costly than Optimal Response: $\mathbb{E}W^{OR} - \mathbb{E}W^{Banking} = O(1)$.

1.B.3 Proof of Theorem 1

1.B.3.1 Optimal Response

The Optimal Response is defined through the competitive equilibrium condition $\forall m = 1, ..., N : p_m = \theta_m - \beta q_m$, rational expectations $\forall 1 \le m \le n \le N : \mathbb{E}_m p_n = p_m$, and expected efficiency $p_m = \gamma \mathbb{E}_m Q$. These properties enable us to construct the dynamics for prices and quantities. Optimal Response solves the set of equations $B'_m = \mathbb{E}_m B'_{m+1} = \mathbb{E}_m B'_{m+2} = ... = \mathbb{E}_m B'_N = \mathbb{E}_m C'$, where competitive markets ensure $B'_n = p_n$:

$$\mathbb{E}_m B'_n = \alpha^{\frac{n-m}{N-1}}\theta_m - \beta \mathbb{E}_m q_n \tag{1.42}$$

$$\mathbb{E}_m C' = \gamma Q_m + \frac{\gamma}{N}\sum_{n=m+1}^{N} \mathbb{E}_m q_n \tag{1.43}$$

for $Q_m = \sum_{n=1}^{m} q_n/N$. We multiply the first equation by $\frac{\gamma}{N\beta}$, sum over all curent plus future $n = m, ..., N$, add the second equation, write $\mathbb{E}_m p_N$ for expected marginal benefits and costs, to get:

$$\left(1 + \frac{\gamma}{\beta} x_m\right)\mathbb{E}_m p_N = \gamma Q_m + \frac{\gamma}{\beta} A_m \theta_m \tag{1.44}$$

where $x_m = (N - m + 1)/N$ is the share of remaining periods (including period m), and $A_m = \sum_{k=m}^{N} \alpha^{\frac{k-m}{N-1}}/N$ is the cumulative increase in current plus future marginal productivity induced by θ_m. Combining with the price equation (1.5), is rewritten as

$$p_m = \frac{\beta\gamma}{\beta + \gamma x_m} Q_{m-1} + \frac{\gamma}{\beta + \gamma x_m} A_m \theta_m \tag{1.45}$$

$$q_m = \frac{-\gamma}{\beta + \gamma x_m} Q_{m-1} + \frac{1}{\beta}\left(1 - \frac{\gamma}{\beta + \gamma x_m} A_m\right)\theta_m, \tag{1.46}$$

which gives the recursive solution, $p_m^{OR}(Q_{m-1}, \theta_m), q_m^{OR}(Q_{m-1}, \theta_m)$.

Note that because the OR does not equalize prices over periods, and thus the prices follow a random walk, there is a non-vanishing welfare loss relative to the Social Optimum: $\mathbb{E}W^{OR} - \mathbb{E}W^{CQ} = O(1)$.

1.B.3.2 Responsive Quota

Responsive quota has the same allocation as OR for $m = 1, ..., N-1$, but for the last period

$$p_N = p_{N-1} + \mu_N, \tag{1.47}$$

$$q_N = \frac{\alpha^{\frac{1}{N-1}}\theta_{N-1} - p_{N-1}}{\beta}. \tag{1.48}$$

At the last period, there is history of cumulative emissions Q_{N-1}, an expected demand increase $\alpha^{1/(N-1)}\theta_{N-1}$, and a final demand shock $(1-\alpha^{2/(N-1)})^{1/2}\mu_N$. The Optimal Response fully adapts quantities and prices (q_N, p_N) to the new information μ_N. The Responsive Quota fixes last-period quantities q_N to the expected level. Thus, in the multi-period model, welfare losses of Responsive Quota compared to the Optimal Response can only arise in the last period. Formally, as $(Q^{OR} - Q) = (q_N^{OR} - q_N)/N$ the welfare gap becomes (where we leave the RQ superscripts):

$$\mathbb{E}W^{OR} - \mathbb{E}W = \mathbb{E}\left[\frac{1}{2N}(p_N^{OR} + p_N)(q_N^{OR} - q_N) - \frac{\gamma}{2N}(Q^{OR} + Q)(q_N^{OR} - q_N)\right] \tag{1.49}$$

Since $\mathbb{E}(q_N^{OR} - q_N) = \mathbb{E}_{N-1}(q_N^{OR} - q_N) = 0$, we can multiply it by a constant $\mathbb{E}_{N-1}p_N^{OR}$, $\mathbb{E}_{N-1}p_N$, $\mathbb{E}_{N-1}q_N^{OR}$ or $\mathbb{E}_{N-1}q_N$, keeping zero. Also, when it is multiplied by Q, the part multiplied by Q_{N-1} is zero and only the interaction with q_N remains. Thus, the above equation transforms into

$$\mathbb{E}W^{OR} - \mathbb{E}W = \mathbb{E}\left[\frac{1}{2N}\Big((p_N^{OR} - \mathbb{E}_{N-1}p_N^{OR}) + (p_N - \mathbb{E}_{N-1}p_N)\Big)(q_N^{OR} - q_N)\right] \tag{1.50}$$

$$- \mathbb{E}\left[\frac{\gamma}{2N^2}\Big((q_N^{OR} - \mathbb{E}_{N-1}q_N^{OR}) + (q_N - \mathbb{E}_{N-1}q_N)\Big)(q_N^{OR} - q_N)\right], \tag{1.51}$$

where the division by N^2 in the second line appears because of production aggregation specified in (1.19). On closer inspection, the above resembles exactly the first line of (1.35). That is, welfare losses of Responsive Quota relative to the Optimal Response equal those of Quota relative to the Social Optimum in a one-period model with noise μ_N, marginal costs slope γ/N, and divided by N to correct for the shorter length of period. Thus, we can take the second line of (1.35) and transform it into

$$\mathbb{E}W^{OR} - \mathbb{E}W^{RQ} = \frac{-1}{2N(\beta + \gamma/N)}(1 - \alpha^{2/(N-1)})\sigma^2 \tag{1.52}$$

In the limit, we have $N(1 - \alpha^{2/(N-1)}) \to -2\ln(\alpha)$, so that

$$\lim_{N\to\infty} N^2(\mathbb{E}W^{OR} - \mathbb{E}W^{RQ}) = \frac{-\ln(\alpha)}{2\beta}\sigma^2. \tag{1.53}$$

Another way to write this is $\mathbb{E}W^{OR} - \mathbb{E}W^{RQ} = O(N^{-2})$, the second result of Theorem 1.

1.B.3.3 Endogenous Taxes

Endogenous Taxes has the same allocation as OR for $m = 1, ..., N-1$, but for the last period we have $p_N = p_{N-1}$ and

$$q_N = \frac{\theta_N - p_{N-1}}{N\beta}. \tag{1.54}$$

To determine the welfare losses relative to OR, we follow the same argument as for RQ. OR optimally determines last-period allocation q_N, p_N, while the Endogenous Taxes fixes last-period prices p_N to the expected level. Thus, welfare of Endogenous Taxes compared to the Optimal Response has the same welfare losses as Prices in the one-period model (1.37), but with γ replaced by γ/N, and divided by N to account for the period length:

$$\mathbb{E}W^{OR} - \mathbb{E}W^{ET} = \frac{-\gamma^2}{2N^3\beta^2(\beta + \gamma/N)}(1 - \alpha^{2/(N-1)})\sigma^2. \tag{1.55}$$

In the limit, this gives us

$$\lim_{N\to\infty} N^4(\mathbb{E}W^{OR} - \mathbb{E}W^{ET}) = \frac{-\gamma^2 \ln(\alpha)}{2\beta^3}\sigma^2, \tag{1.56}$$

restated as the first result of Theorem 1: $\mathbb{E}W^{OR} - \mathbb{E}W^{ET} = O(N^{-4})$.

CHAPTER 2

An Endogenous Emissions Cap Produces A Green Paradox

2.1 Introduction

In order to reduce greenhouse gas emissions economists have long advocated carbon pricing, either as a tax or via an emissions trading system (ETS) [c.f. 5, 61]. Where a tax fixes the price of emissions, an ETS sets overall emissions while leaving the price endogenous to forces in the market. The typical ETS in addition allows for banking and, sometimes, borrowing between periods. With banking and borrowing, short-run emissions levels can flexibly adjust to changing market conditions even if the short-run supply of emissions allowances is fixed. Long-run emissions levels are still given, however, as long as the long-run supply of allowances is exogenous.

Emissions targets are a natural focal point of policy making and, perhaps for this reason, policy makers around the world have generally favored ETSs over emissions taxes. The aim of any climate policy is to halt global warming by reducing greenhouse gas emissions. In this sense, an emissions cap like the European Union's Emissions Trading System (EU ETS) or the Regional Greenhouse Gas Initiative (RGGI) is the most direct instrument toward the given goal of limiting emissions.[1] While an emissions tax can, in the end, also achieve a reduction in emissions, the effect is indirect. In addition, a cap offers certainty on emissions whereas a carbon tax leaves the realized amount of emissions reduction to the market, which can be politically undesirable. Finally, in the context of the European Union, an emissions cap can be imposed after simple majority voting whereas an EU-wide tax requires unanimous consent.[2]

Due to uncertainty, the realized ETS price may exceed, or fall short of, prices expected

[1] The Regional Greenhouse Gas Initiative is "a cooperative effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont to cap and reduce CO_2 emissions from the power sector." (retrieved from www.rggi.org).

[2] I.e. a carbon tax would fall under each national government's sovereignty whereas an ETS can be established under supra-national EU law.

when the system is set up [140]. To avoid sustained unexpected deviations of emissions prices, supplementary measures have been proposed or even implemented, such as price collars [1, 23, 130] or endogenous allocation of allowances to individual firms (e.g., output-based allocation, cf. Böhringer et al. [20], Fowlie et al. [50]). The EU ETS, the world's largest operating carbon market, recently implemented involving market-induced cancellation of allowances. Hence, the long-run supply of allowances is no longer fixed — the emissions cap is endogenous by construction [55, 124].

In this paper we show, first analytically in a simple two-period model and then numerically in the context of the EU ETS, that an emissions trading system with a quantity-based endogenous cap produces a green paradox. More precisely, we show that there exists an abatement policy which reduces the demand for allowances but at the same time increases aggregate emissions. When calibrating and simulating a model of the EU ETS, we find that the green paradox may be substantial, especially if demand for emissions allowances is reduced only several years from now but anticipated already today. Our results clearly show that the announcement of future abatement policies can invert the long-run effects from a reduction to an increase in emissions.

The endogenous supply of allowances in the EU ETS is itself endogenous to its history. Over the years from 2008 to 2012, the net supply of allowances increased through a large inflow of certified emissions reductions from clean development mechanism (CDM) projects. Besides, and due to the economic slowdown that started in 2008, demand for allowances decreased and a large amount of banked (i.e. unused and saved for later) allowances accumulated. The large bank exercised a downward pressure on the price of emissionsallowances (EUAs), which dropped below 10 €/tCO_2 from 2012 onward. Perceiving these prices as too low, the EU implemented a Market Stability Reserve (MSR) in 2015. The ides of this MSR is that if aggregate banking in the market exceeds a certain threshold, part of next year's allowances enter the MSR rather than the market [44, 90]. These MSR-held allowances are to be 'backloaded' in the future, when demand is higher. Importantly, though, note that this initial MSR only reduced the short-run supply of allowances – the long-run, cumulative cap on emissions remained untouched.

Leaving the cumulative cap untouched, the backloading of allowances did not create more scarcity and thus did not succeed to push up prices. In response, the EU adapted the following MSR-mechanics in 2018: when the size of the MSR exceeds the annual level of auctioned allowances, all allowances above this threshold are permanently canceled. With this adjustment to the MSR, the cumulative cap was effectively reduced, supporting higher prices. Importantly, the amount of canceling has been made endogenous; it depends on the allowances that are banked and subsequently flow into the MSR. Intertemporal supply and demand now find themselves in a delicate balance.

Whereas abatement policies had no effect on cumulative emissions under the old regime, Perino [124] finds that the new rules (as intended) leave them some leverage. A one ton demand reduction in 2018 reduces cumulative emissions (i.e. the long-run emissions cap) by 0.4-0.8 tons according to his calculations. The reasoning is that reduced demand in 2018 increases banking and a bigger inflow into the MSR, which eventually cancels more allowances. That is, the new MSR rules have 'punctured the waterbed'.[3] The magnitude of the effects depend on the timing of the demand reduction, and the time window over which the MSR takes in allowances.

Gerlagh and Heijmans [55] extend the analysis by Perino [124] and consider changes in equilibrium prices as well as second-order effects on banking and allowance cancellation. In the present paper, we add one more element and examine the effects of demand reductions in any period, differentiating between surprise policies and those anticipated before implementation.

With respect to unanticipated policies, our analysis underscores Perino's (2018) finding that emissions-reducing policies are (partially) effective. A surprise policy that reduces the demand for allowances also reduces cumulative emissions if it is announced and implemented at the same time. This conclusion changes drastically when considering anticipated future policies instead [cf. 131]. If the policymaker announces a complementary emissions-reducing policy today that will be implemented some years from now, firms anticipate the associated reduction in demand to come, and reduce the amount of allowances they bank: why keep them for a future in which they are not needed? This is important because, by construction of the EU ETS, a decrease in banking leads to less inflow into the MSR. Furthermore, only allowances in the MSR can be canceled. It follows that fewer emissions allowances get written off. Hence, while the complementary policy reduces future emissions indeed, it also starts an unintended chain of events through which, in the years leading up to the reduction, emissions increase. If the policy is anticipated long enough in advance, this causes cumulative emissions to be higher compared to the case in which no policy had been implemented.

The mechanism we described is somewhat reminiscent of the green paradox [19, 136]: anticipated future climate policies incentivize fossil fuels producers to speed up extraction, increasing current but not cumulative emissions. In our context, it is not the timing of emissions but cumulative emissions that increase following well-intended climate policies [cf. 52]. The green paradox we consider is therefore stronger than the classic one, and caused by an artificial market intended to support climate policies.

[3] If the emissions cap is fixed and binding, any additional policies will not affect total emissions, but only shuffle emissions around. This is often referred to as the waterbed effect: Sitting on a waterbed changes the distribution of water inside the bed, but not the total amount of water the bed contains.

Importantly, our result does not warrant the conclusion that an endogenous emissions cap like in the EU ETS is a bad idea per se. Rather, it illustrates the cost of leaving out all price information from the MSR design.[4] Quantity-related targets are politically manageable, while price-related regulation is politically sensitive, particularly in the EU. But the resulting pure quantity-based regulation does not interact well with overlapping policies, especially when these are announced in advance of actual implementation. Constructively, we therefore suggest several relatively straightforward fixes to the EU ETS that remedy our green paradox. Most simply, the European Commission could complement any demand-reducing policy with a proportionate decrease in the future supply of allowances. Alternatively, the EU ETS could be enhanced with a price mechanism such that the supply of allowances is reduced when the allowance price falls.[5] We discuss the relative merits of these solutions at some length in Section 2.5.

Only a few published studies exist quantifying the impacts of the cancellation rules in the MSR, and none of them consider the green paradox we demonstrate. The first quantitative study is probably [126], who simulated the impacts on EUA prices of the (then) proposal to cancel allowances, extending the model in [125]. [135] use a quantitative model similar to ours, concluding that demand-reducing policies in early years reduce cumulative emissions. They find bigger quantitative impacts than Perino (2018), as the MSR takes in allowances for a much longer period (we find similar results in this paper). [24] use a more detailed model of the EU ETS and investigate the impacts of the MSR on EUA prices and cumulative emissions. [54] apply the same model as in this paper, examining the impacts of COVID-19 on EUA prices with and without the cancellation rules.

Our results invite particular concern in light of recent policy developments. In December 2019, the European Commission presented its 'European Green Deal', promising 50-55% reductions in greenhouse gas emissions compared to 1990 levels in 2030, and a carbon neutral economy by 2050 [42].[6] While setting an ambitious agenda, the European Green Deal is precisely the kind of demand-reducing policy, announced and anticipated years in advance of actual implementation, to which our findings speak. Unless changes to the EU ETS are implemented in parallel, the announced demand-reductions in future decades may backfire. They may reduce the inflow into the MSR in the near future, reducing cancellation of emissions allowances, eventually increasing cumulative emissions within the EU ETS.

[4] Note that the intuition we presented above for the green paradox, caused by the MSR, did not refer to prices.

[5] This does not need to be a rigid price floor as in the Regional Greenhouse Gas Initiative. The auctioned volume can continuously decrease with decreasing prices.

[6] In December 2020, the EU Heads of State approved an emissions reduction target of at least 55% for 2030, cf. https://ec.europa.eu/commission/presscorner/detail/en/mex_20_2389.

On the other hand, a fairly simply remedy to our green paradox result exists. If the policy maker, upon announcing a demand-reducing policy, simultaneously reduces the supply of allowances, this can undo the green paradox effect. Such a supply-reduction can be implemented either at the EU level through a more rapid reduction in the annual supply of allowances, or at the national level through unilateral cancellation of allowances.[7] Such an adaptation retains the efficiency benefits of an endogenous supply scheme as implemented into the EU ETS yet mitigates the problems due to a green paradox identified in the present paper. We come back to ETS policies complementing demand-reducing measures when discussing our findings in the Section 2.4.

The structure of the paper is as follows. We first present a stylized two-period model in which we lay out the mechanisms that lead from the endogenous cap to a green paradox. The next section adds the details of the EU ETS. A particular element of the EU ETS cum MSR is that it exhibits multiplicity of equilibria, and that the green paradox specifically arises for abatement policies that reduce future demand. We showcase these elements through a numerical calibration to the model, in which we calculate the size of the green paradox in the EU ETS. In Section 2.4, we present discuss the policy implications of our results, as well as several fixes. The final section concludes.

2.2 Model

Let there be two periods $t = 1, 2$, and let e_t denote the emissions in period t. Because firms have to surrender allowances, or permits, for their emissions, we save on notation and let e_t denote the demand for allowances as well. Permits are traded at a price p_t and we allow for banking and borrowing of allowances between the two periods.[8]

Demand for allowances e_t is decreasing in the price p_t and we describe this relationship via the demand function $f_t(p_t)$. We also leave room for demand reductions that are external to the ETS itself, such as shifts in consumer preferences toward less emission-intensive products or complementary policies affecting the demand for emissions altogether (e.g. the European Green Deal, phasing out of coal power, or supporting zero emissions technologies). Let λ_t denote these external effects, such that $\lambda_t < 0$ describes a *reduction* in demand. We will refer to λ_t as a complementary demand policy in our narrative. With these elements, we obtain the following demand for

[7]The German government is planning to cancel allowances along with the country's phase-out of coal power. At the time of writing, it is not decided how many allowances will be canceled, but the government stated it will take into account cancellation of allowances via the MSR when making the decision [137].

[8]In the EU ETS, borrowing from a future period is not allowed. However, this constraint is currently not binding, and will probably not be binding in the foreseeable future (nor in our simulations).

allowances:

$$e_t = f_t(p_t) + \lambda_t. \tag{2.1}$$

Aggregate emissions E are equal to the sum of emissions in the two periods: $E = e_1 + e_2$. We are particularly interested in $dE/d\lambda_t$, that is, the effect of a demand-reducing policy on aggregate emissions. If $dE/d\lambda_t = 0$, we have the standard waterbed effect, and the policy can be regarded as ineffective. If $0 < dE/d\lambda_t < 1$, the policy is (slightly) effective, while there is a green paradox if aggregate emissions *increase* in response to a demand-reducing policy, $dE/d\lambda_t < 0$.

The demand function given by (2.1) can be inverted to yield an inverse demand function $\psi_t(.)$:

$$p_t = \psi_t(e_t - \lambda_t). \tag{2.2}$$

While it is not necessary to assume price-taking behavior, for the sake of analytical convenience we make the standard assumption that the price rises by the interest rate r:

$$p_2 = (1 + r)p_1. \tag{2.3}$$

This condition is known as Hotelling's Rule and follows from free banking of allowances over time (see footnote 8) combined with unrestricted access by outsider firms to ETS allowances. It describes intertemporal arbitrage between investment opportunities [82]. If the price would rise at a pace above the interest rate, investors would have an incentive to buy allowances in the first period, and sell them in the second period at a positive net return. But this would lead to a rise in the first period price and a decrease in the second period price, and equilibrium would not be reached until the allowances price rises by the interest rate. A similar reverse mechanism prevents prices from rising below the interest rate.[9]

Note that a complementary demand-reducing policy in a given period ($\lambda_t < 0$) suppresses the price of emissions in that period. The implication of Hotelling's Rule is then that the price of emissions in the other period ($s \neq t$) should fall as well, which means that emissions in period s will rise. Without the MSR, the emissions reductions in period t would be completely undone through increased emissions in period s, i.e., the waterbed effect. With the MSR, things are not as straightforward as we shall see below.

Hotelling's Rule is intimately related to the ease with which a more ambitious climate policy can be implemented today compared to the future. To see this, consider a one

[9]That is, free access for outsiders to the allowances market reduces the feasibility of strategic price-distorting behavior by firms in the market.

unit reduction in cumulative emissions, $dE = de_1 + de_2 = -1$. The change in prices per unit additional emissions reduction in period 1 is given by ψ_1', the slope of the inverse demand function in the first period (cf. (2.2)). Similarly, bringing about one unit additional emissions reductions in the second period would change prices in that period by ψ_2'.

For a given additional tightening of emissions, the ratio between these price effects can be viewed as a measure for the relative difficulty of reducing emissions in the first period compared to the second. In economic terms, we are interested in the ratio of the elasticity of demand, as a measure of the relative effort of a first-period reduction vis-a-vis a second-period reduction:

$$\eta = \frac{\psi_1'/\psi_1}{\psi_2'/\psi_2} = \frac{(1+r)\psi_1'}{\psi_2'}. \tag{2.4}$$

An efficient allocation of the climate ambition splits the additional emissions reduction between the two periods such that the marginal costs rise by the interest rate (the relation to Hotelling's Rule suggested earlier). If $\eta < 1$, an efficient policy reduces emissions mostly in the first period. If $\eta > 1$, increased climate ambitions will mostly reduce demand for allowances in the second period.

While so far our focus has been on the demand for emissions allowances, these must be matched by supply in the ETS. Let supply be given exogenously by $\overline{s}_t$ in t. If a firm has more allowances in the first period than it uses, it can bank these allowances for use in the second period. Let this bank, aggregated over all firms, be denoted b, so that $b = \overline{s}_1 - e_1$. The level of banking is crucial for the operation of the MSR, and a detailed explanation of this is given in the next section. For our model, we rely on a stylized representation. If the bank exceeds some given threshold $\overline{b}$, so $b > \overline{b}$, then the supply of allowances in the second period is reduced by an amount δb; a fixed fraction of the total bank.[10] Importantly, firms keep their (private) bank of allowances. Banked allowances are not canceled and so Hotelling's Rule, (2.3), is maintained. This, in turn, means that firms' banking incentives are not directly affected.[11] Rather, the supply of *new* allowances in the second period is adjusted; supply drops to $\overline{s}_2 - \delta b$.

Supply and demand of allowances must balance in an ETS, which leads to the following set of conditions:

$$e_1 + b = \overline{s}_1, \tag{2.5}$$

[10]Note that the EU ETS without MSR-driven canceling of allowances is effectively described by setting $\delta = 0$ in our model. Note also the discontinuity around $\overline{b}$ - supply drops by $\delta\overline{b}$ units as banking crosses $\overline{b}$.

[11]If a policy were to touch the allowances held by private firms, it would disturb abatement incentives away from Hotelling's Rule and that is inefficient. Quantity-based policies to remedy a perceived over-supply of allowances can therefore be efficient only if they reduce the net supply ot allowances directly, without touching allowances held by private firms.

$$e_2 = \overline{s}_2 + b \qquad \text{iff } b \leq \overline{b}, \tag{2.6}$$

$$e_2 = \overline{s}_2 - \delta b + b \qquad \text{iff } b > \overline{b}. \tag{2.7}$$

For now, we assume that the bank exceeds the cancelation threshold: $b > \overline{b}$. We return to this assumption below, though we note that it is clearly met in the real EU ETS. Since total emissions equal total supply as well, we then obtain from (2.5) and (2.7):

$$E = e_1 + e_2 = \overline{s}_1 + \overline{s}_2 - \delta b. \tag{2.8}$$

Equation (2.8) highlights an important implication of the MSR: cumulative emissions *decrease* proportionally with banking. Since banking decreases in first period demand, this means that low demand in the first period leads to decreased supply in the second, and therefore to a decrease in cumulative emissions. This is the essence of the EU ETS' stability mechanism.

Observation 1. *The change in cumulative emissions equals the change in banking in the first periods, multiplied by the cancelation parameter δ (as long as $b > \overline{b}$):*

$$dE = -\delta db = \delta de_1 \tag{2.9}$$

We can now derive our key results as an implication of the simplified model developed in this section. Imagine that the government enacts a complementary demand-reducing policy in the first period: $\lambda_1 < 0$. This policy, by its nature, reduces the demand for emissions in period 1 ($e_1 \downarrow$). The decline in demand mechanically leads to more banking ($b \uparrow$), which in turns leads to less supply of allowances in the second period through the MSR ($\overline{s}_2 - \delta b \downarrow$). Consequently, emissions overall will fall ($E \downarrow$). This result is as intended: a policy reducing the demand for emissions leads to lower cumulative emissions.

The more counter-intuitive case arises when the government enacts a complementary demand-reducing policy in the second period, $\lambda_2 < 0$, which is announced (or at least anticipated) in the first. Anticipating a lower demand for allowances in the second period ($e_2 \downarrow$), firms will bank fewer allowances in the first period for use in the second ($b \downarrow$). This decreased banking implies a lower reduction of supply in the second period through the MSR ($\overline{s}_2 - \delta b \uparrow$). Aggregate emissions rise accordingly ($E \uparrow$). This, at first, is a counter-intuitive result: a policy reducing demand for emissions *in the second period* leads to higher emissions overall.

Proposition 2 formalizes these discussions.

Proposition 2 (Green Paradox)**.** *Assume that $b > \overline{b}$. Then we have:*
The MSR retains but dampens the effect of demand-reducing policies in the first period:

$$0 < \frac{dE}{d\lambda_1} = \frac{\delta\eta}{\eta + 1 - \delta} < 1. \tag{2.10}$$

The MSR reverses the effect of demand-reducing policies in the second period:

$$\frac{dE}{d\lambda_2} = -\frac{\delta}{\eta + 1 - \delta} < 0 \tag{2.11}$$

The proofs of this and the next proposition are found in Appendix 2.A.

Recall that our stylized model of the EU ETS *with* MSR can also describe a situation *without* MSR by setting the cancellation-parameter $\delta = 0$. In this case, demand-reducing policies in either period have no effect on emissions: the waterbed effect.

With positive canceling of allowances, $0 < \delta < 1$, Proposition 2 tells us that demand-reducing policies in the first period indeed lower cumulative emissions: the waterbed is punctured with respect to early supplemental climate policies [*cf.* 124]. A green paradox arises when the government enacts demand-reducing policies in the second period that are anticipated in the first, for then cumulative emissions increase.

In the special case of complete cancellation, $\delta = 1$, the waterbed is not just punctured for early demand reductions: it is leaking altogether. For, as Proposition 2 makes clear, in this case early demand-reducing policies are fully translated in aggregate emissions reductions ($\frac{dE}{d\lambda_1} = 1$). On the downside, complete cancellation also leads to a sizable green paradox. Indeed, if the cost of achieving increased climate ambitions today is relatively low compared to achieving the same ambitions in the future ($\eta < 1$), our green paradox exceeds 100 percent: reducing demand in the second period by 100 ton of CO_2 leads to a more than 100 ton increase in aggregate emissions!

We note that our green paradox is not due to an accidental and unfortunate combination of factors in the EU ETS. It is a fundamental feature of any endogenous emissions cap that works through quantities (i.e. some $\delta \neq 0$), rather than through price information. This suffices to understand the economics behind the green paradox that arises in our simulations. For completeness we graphically illustrate Proposition 2 in the Appendix 2.A, see the left panel of Figure 2.6.

There is one thing left to be discussed. Our simple model also illustrate an unwanted side effect of *discrete* supply-adjustments in response to trigger events. In the EU ETS, supply in the second period is not necessarily continuously reduced in response to banking. Rather, the marginal effect of banking on supply reductions jumps *discretely* when banking crosses the cancellation threshold $\bar{b}$. To be more precise, for all banking levels $b < \bar{b}$, there is no cancellation of allowances in the second period, whereas for all banking levels $b > \bar{b}$, supply in the second period is reduced by an amount δb. Hence, when banking crosses the threshold $\bar{b}$, the cancellation of allowances in period 2 jumps up from zero to some amount at least $\delta\bar{b}$. This discrete adjustment of supply may lead to unexpected problems of uniqueness or existence. See the appendix, Fig 2.6 right panel, for a graphical representation. The next proposition formalizes.

Proposition 3 (Multiplicity). *If an equilibrium exists with banking sufficiently close to the threshold, $|b - \overline{b}| < \varepsilon$ and ε small, then at least two distinct equilibria exist. These equilibria are supported by distinct price-paths $(p_1^*, p_2^*) < (p_1^{**}, p_2^{**})$, and different levels of cumulative emissions $E^* > E^{**} + \delta\overline{b}$.*

The problem with equilibrium multiplicity is the inherent unpredictability of the market it implies. A policy maker expects firms to behave according to the equilibrium of the (implicit) game they are playing. But if there is more than one equilibrium, which outcome should the policy maker expect? Worse still, what should firms expect other firms to do? This leads to an intricate system of expectations with no clear outcome. Firms are essentially forced to act by guess and by golly, which may lead to coordination failure and inefficiency [139].

In addition to equilibrium multiplicity and coordination failures, discrete supply-adjustments are undesirable as they invite participating firms to engage in strategic gambling. While the consequences of such behavior are hard to assess without clear data, there is experience with it in other domains; currency attacks reveal the potential for private gains from exploiting policy interventions triggered by market indicators [113]. In the context the EU ETS, suppose the expected bank size at the end of the year is slightly below the threshold that triggers a flow into the MSR. A large firm could then buy a substantial number of allowances, driving up the price by a small amount. This leads to a reduction in demand for other firms and could thus push the bank above its MSR-threshold, inducing a large write off of allowances through the MSR. After the market switches to a new equilibrium, the large firm can then sell its allowances at a higher price and book a substantial gain. In this sense, discrete trigger events build a kind of strategic complementarities [25] into the game.

The EU ETS is not the only system where trigger events lead to discrete adjustments in supply. RGGI admits a similar property: the supply of allowances is reduced by a *discrete* amount when prices fall below a specific level. RGGI, too, may therefore be susceptible to equilibrium multiplicity.

Propositions 2 and 3 are not intended to constitute a criticism of endogenous emissions caps altogether. For a pollutant with the characteristics of climate change, where damages dependent on *cumulative* emissions, a reduction of future supply in response to lower current demand yields substantial welfare improvements [53]. Rather than suggesting that the EU ETS abandons its MSR, we therefore argue the MSR mechanics should be adopted to preempt the possible problems we identify. We return to this point later in the paper.

2.3 Quantitative assessment

2.3.1 EU ETS model

In this section we develop and simulate a stylized, dynamic model of the EU ETS that captures the mechanics of the MSR in detail. We first briefly revisit the EU ETS and the rules of the MSR.

EU ETS is the largest market for carbon to date and as one of the first such instruments, it has experienced many difficulties since its conception. Firms under the EU ETS at risk of relocating have led the EU to adopt (too) generous compensation mechanisms [104]. The price of allowances has been consistently low and highly volatile, carrying along some counter-intuitive implications for firms' profit [27]. The low price of carbon in the EU ETS can be traced back to interactions with supplemental climate policies as well as the general economic recession during part of its existence. The cap on emissions has been considered set too loosely, as evidenced by a strong accumulating 'bank' of unused allowances, privately stored by firms for future use, despite the low prices.[12]

In response, the EU introduced a Market Stability Reserve (MSR) and set the new rules in 2018. From 2019 the MSR takes in allowances that are otherwise auctioned, the amount of which equals 24% (12% as of 2024) of banked allowances, every year the (cumulative) bank exceeds 833 $MtCO_2$.[13] These allowances, *not* taken from the private bank of allowances but from the volumes otherwise auctioned, will return to the market later: in years when the bank has shrunk to below 400 $MtCO_2$, an additional 100 $MtCO_2$ is auctioned from the MSR. However, when too many allowances end up in the MSR, all MSR-held allowances in excess of the volume auctioned in the previous year are canceled permanently (starting in 2023). In this sense, the MSR with canceling effectively makes the cap on emissions in the EU ETS endogenous. The MSR reforms have been documented in Perino [124] and Gerlagh and Heijmans [55]. The equations used for our simulations are provided in the appendix, Section 2.B.

Figure 2.1 presents the timeline for the MSR in our calibrated model.[14] From 2019 (t_0) to 2048 (t_2), the MSR takes in allowances, reducing the amount auctioned (as mentioned above, the intake rate is reduced from 24 to 12 percent in 2024). The

[12] [72] suggests that the emissions cap in phase II of the EU ETS was not binding, as thus the nonzero price toward the end of the phase "reflected expectations of a cap on overall emissions that is binding in the long term, given the opportunity to bank allowances".

[13] The EU has introduced the term "Total number of allowances in circulation (TNAC)" ([41]), which for our purpose is equivalent with private banking of allowances.

[14] Whereas the mentioned years are specific to our model, other quantitative assessments of the MSR also tend to find a similar timeline, i.e., an inflow phase partly overlapping with cancellation, followed by an outflow phase (e.g., [24], [135] and [126]).

intake stops in 2048 as the bank drops below 833 $MtCO_2$. From 2023 (t_1) to 2059 (t_3), allowances in the MSR are canceled when they exceed the volume auctioned in the previous year. In 2059, the bank has dropped below 400 $MtCO_2$, and the MSR returns the remaining allowances into the market, for one year (t_4). The ETS lasts till 2066 (T) in our calibrated model. Below, throughout this section, we will use general notation t_i when we emphasize the mechanisms at work. When presenting quantitative numbers, we will refer to years.

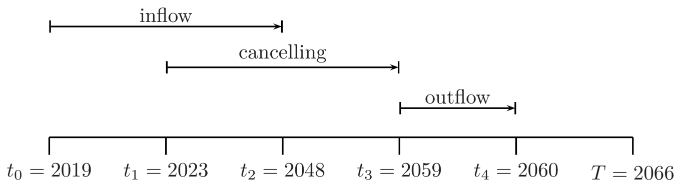

Figure 2.1 – Time line for MSR

We assume allowances have constant assets return $1 + r$ leading to the Hotelling rule for prices (i.e., generalization of (2.3)):

$$p_{t+1} = (1 + r)p_t. \tag{2.12}$$

The ETS is in equilibrium when there are no left-over unused allowances. As the MSR is emptied before the end of the ETS, cumulative emissions are given by cumulative supply minus cancelled allowances. Given the stages displayed in Figure 1, all additions to the MSR before t_2 become cancelled one-to-one. In other words, if some policy or other economic changes move demand from early to late periods, so that banking in early periods increases, such a change in the demand path reduces cumulative emissions. We replicate Observation 1 in the context of the EU ETS:

Observation 2. *The change in cumulative emissions equals the change in banking in periods before t_2, multiplied by the shaving parameter (24 percent before 2024, 12 percent after).*

The observation tells us why the timing of demand shocks is important for the final effect on emissions. The mechanism is the same as in Section 2: Early demand reductions, while not 100% effective, still lead to an increase in banking and a strictly positive fall in emissions in the aggregate. Late shocks, on the other hand, when anticipated today, lead to a decrease in banking, and thus to an increase in emissions. The increase in demand in early periods is effectively taken from the allowances otherwise canceled from the MSR. Thus, net emissions increase relative to the case where no future reduction in emissions demand had occured. A green paradox arises. We will come back to the importance of anticipation in the next section (see Figure 2.4).

One important condition for our green paradox is that the demand-reducing policy implemented in the future is anticipated today, so a forward-looking agent takes the future drop in demand (or prices) into consideration when making decisions on banking. For "surprise demand reduction" in the second period, the result does not hold. This insight highlights the importance of policy announcement. While the timing of a policy matters, the timing of its announcements matters as well.

2.3.2 Model calibration

We now calibrate a stylized, dynamic model of the EU ETS. We then use this model to quantify the effects discussed in Secion 2.2.

The model is given by the equations in Appendix 2.B, and is conceptually similar to the analytical model in Secion 2.2 (but with more periods and more detailed modeling of the MSR). Here we focus on the specification and calibration of the demand function, which we specify as follows:

$$e_t(p_t; \lambda_t) = (a - bp_t)(1 + ct) + \lambda_t, \tag{2.13}$$

where a, b and c are three parameters to be calibrated. a/b is the (constant) choke price (that is, the price at which demand equals zero), $1/b$ is the initial slope of the inverse demand function, and c determines how the demand function changes over time (for a given price). Parameter specifications are shown in Table 2.1 in the appendix. Here we give a brief explanation of how the model is parameterized.

To estimate the demand function, the three parameters are disciplined using historic evidence. We require that the following three conditions are met: i) the level of demand should be consistent with the observed price and demand combination in 2018; ii) the simulated Base Case scenario, which includes the MSR, should have an initial price of 21.0 €/tCO_2 in 2019; and iii) a simulated scenario that does not include the MSR should have an initial price of 7.5 €/tCO_2 in 2019. In other words, the model should be able to reproduce both the current ETS prices but also those before the new MSR rules were introduced. We take the real interest rate to be 5 percent.[15]

[15]It is difficult to know what the appropriate interest rate should be. On the one hand, there exists a market for future allowances from which one can derive the discount rate, revealing low returns (for instance, at the time of writing, the future price in December 2026 is 7.2% higher than the future price in December 2021, indicating a nominal interest rate of 1.4% per year, cf. https://www.barchart.com/futures/quotes/CK*0/futures-prices). On the other hand, the future of the EU ETS is uncertain, suggesting a higher rate. Our choice of 5% is 'middle of the road' compared to the literature.

The calibration leads to a choke price of 221.5 €/tCO_2. Further, the annual shift in the demand function is -2.1% (of initial demand). Taken together, this means that demand (i.e., emissions) becomes zero by 2066. Annual gross supply (s_t) becomes zero after 2057, assuming a continuation of the linear reduction rate after 2020. For this reason, we calibrate the final year in which the EU ETS is operative to be 2066 in our calibrations.

2.3.3 Quantitative results: Baseline scenario

The model described above can easily be simulated to derive the EU ETS market equilibrium for the period 2019-2066.[16] The outcome is shown in Figures 2.2 and 2.3.[17] Note that this should not be taken as a forecast of the EU ETS market. The purpose of this analysis is to examine the effects of demand-reducing policies at different points of time, given a possible but fairly realistic scenario for the future EU ETS market.

Figure 2.2 shows that supply exceeds demand until 2050 – which then reverses. Annual demand is equivalent with annual emissions, while supply refers to gross supply (s_t), i.e., before taking into account interaction with the MSR. Initially, net supply is significantly below gross supply (see Figure 2.2), and also well below demand, due to a large inflow into the MSR.

Figure 2.3 shows the stocks of allowance reserves, both privately held ("banking") and in the MSR. It also displays how allowances enter into, or are taken out of, the MSR, as well as the canceled allowances. There is a notable change in 2023-24, due to two important factors those years: Cancellation of allowances begins in 2023 (t_1), and the withdrawal rate drops from 24 to 12 percent in 2024. The latter explains the decline in allowances entering the MSR in 2024 (labeled "MSR-in" in Figure 2.3, labeled m_t in (2.19)), corresponding to the increased net supply (Figure 2.2). In this scenario, the MSR stops taking in allowances after 2048 (t_2), increasing net supply the next year (Figure 2.2). Cancellation of allowances is clearly biggest in 2023, but continues for more than three decades in this scenario. In total, 6.9 Gt of allowances are canceled until cancellation ends in 2059 (t_3), of which 3.6 Gt are canceled by 2030.[18]

[16]The model is simulated using the MCP solver in GAMS (Brooks et al., 1996). The GAMS program is provided in Appendix 2.D.

[17]By assumption, the ETS price starts at 21 Euro per ton in 2019, and reaches 208 Euro in 2066 (due to equation (2.12)).

[18]As a comparison, Refinitiv Carbon (2018) expects 3.3 Gt to be canceled by 2030, and a total surplus of allowances of 1.6 Gt in 2030 (banking in the market plus MSR) implying further cancellation post-2030, especially since that study predicts a rising surplus in the market between 2025 and 2030.

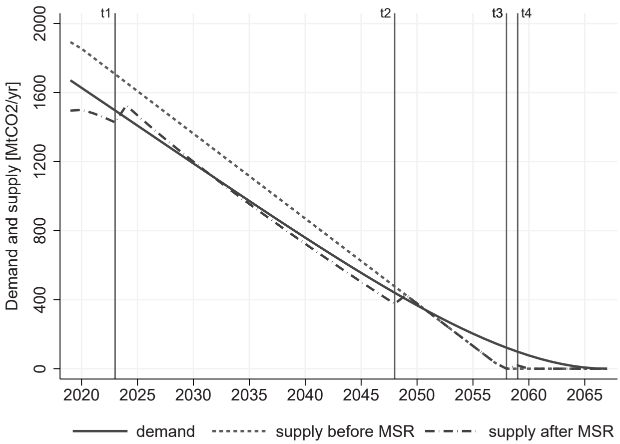

Figure 2.2 – Market balance in Baseline scenario. Annual figures for the period 2019-2066.

2.3.4 Quantitative results: Effects of demand-reducing policy

We now turn to the main purpose of the numerical analysis, which is to examine the effects on cumulative emissions of a demand-reducing policy. We consider policies that reduce demand in a given year t ("reduction year") by one million EUAs (corresponding to 1 $MtCO_2$). Moreover, the announcement of the policy can take place in any year s ("announcement year") up to the year when the demand reduction takes place ($s \leq t$).

Figure 2.4 shows the effect on cumulative emissions of such a demand-reducing policy. On the horizontal axis, we have the reduction year t. The curve “Announcement 2020” shows the effects on cumulative emissions of announcing the policy in 2020 ($s = 2020$), and we have similar curves for $s = 2025$ and $s = 2030$. The fourth curve shows the effects of announcing the policy the same year ($s = t$).

We first notice that a demand-reducing policy announced and realized in 2020 will reduce cumulative emissions quite substantially (relatively speaking). A decrease in emissions in 2020 by 1 $MtCO_2$ will reduce cumulative emissions by 0.97 Mt. The intuition is, as explained by Perino (2018), that less emissions in 2020 lead to more banking over many years, which further increases the inflow into the MSR, and subsequently more cancellation of allowances.

Next, we see from the fourth (solid) curve that we get a similar but less pronounced effect as long as the demand-reducing policy is announced the same year, that is, until 2048 (t_2). Afterwards, the MSR does not take in more allowances (in our scenario, cf. Figure 2.3), which means that from 2048 onwards the supply of allowances is fixed.

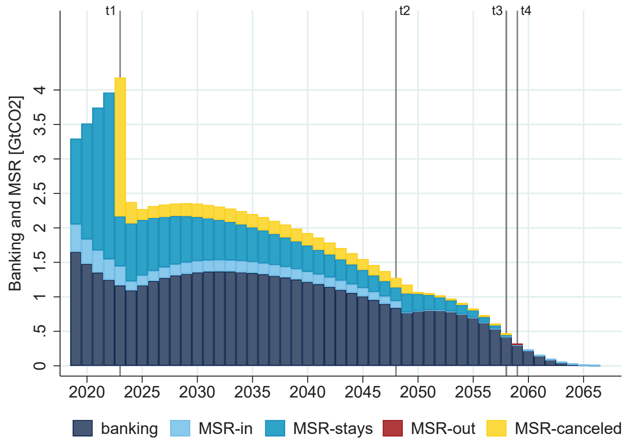

Figure 2.3 – Stocks of allowances. The MSR is divided into the following four contents (cf. eq. 2.19): Input of allowances into MSR this period (m_t, "MSR-IN"); other allowances that remain in the MSR next period ("MSR stays"); allowances that leave MSR next period (n_t,"MSR-OUT"); and allowances that are canceled ("MSR Canceled"). Annual figures for the period 2019-2066 in Baseline scenario. For the meaning of year labels $t1, t2, t3, t4$ see Fig 2.1.

The reason why the effect on cumulative emissions is biggest in the early years is that there are more years with additional inflow into the MSR when banking is increased early on.

If the demand-reducing policy is announced years before it is realized, the effects are quite different though. For instance, if the policy is announced in 2020, but realized in 2048 or later ($t \geq t_2$), the net effect of the policy is to increase cumulative emissions by 0.86 Mt (according to our simulations). That is, the policy has quite the opposite effect of what is intended as it increases rather than decreases total emissions. Hence, a green paradox. The intuition is that when agents in the ETS market foresee a less tight market in the future, it becomes less profitable than before to bank allowances from the preceding periods. With less banking, fewer allowances enter the MSR, and thus fewer allowances become canceled. Moreover, when fewer allowances are taken out of the market, this further reduces the market tightness – hence there is a multiplier effect which is bigger the longer the MSR is taking in allowances.

If the announcement is made in 2025 (or 2030), the effects on cumulative emissions are still perverse, but to a lesser degree as banking before 2025 (or 2030) is not affected. This illustrates the importance of policy announcement. It is not only the timing of the policy that matters, but also the timing of announcement.

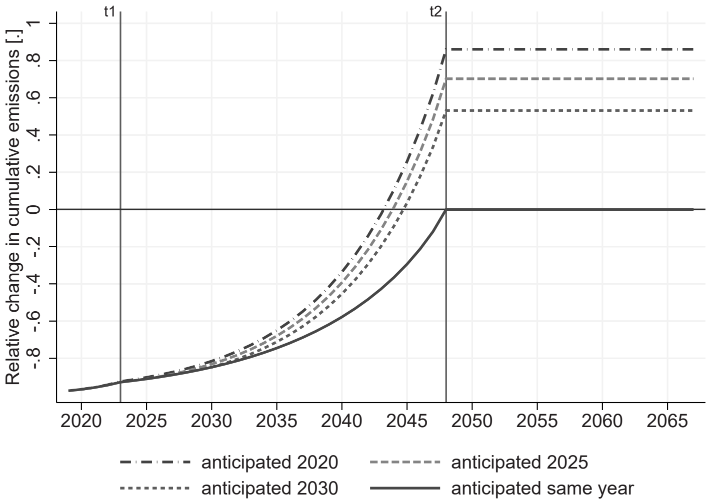

Figure 2.4 – Effects on cumulative emissions of a demand-reducing policy that reduces demand by one million EUAs (1 $MtCO_2$) in the "reduction year" t, with the policy anticipated in year $s \leq t$. Years $t1, t2$ refer to start of canceling in the MSR and the end of the intake, respectively.

We also see from the figure that if the demand-reducing policy takes place in year $\widehat{t}$, where $\widehat{t}$ is only a few years before the MSR stops taking in allowances (t_2), it can still have a perverse effect on cumulative emissions (if it is announced several years in advance). In this case, there will be less banking before, and more banking after, year $\widehat{t}$. Hence, fewer allowances enter the MSR before year $\widehat{t}$, whereas more allowances enter after year $\widehat{t}$. If year $\widehat{t}$ is quite close to t_2, the first effect dominates, and hence the net effect on cumulative emissions is positive.

2.3.5 Quantitative results: Multiple equilibria

In Proposition 3 we noted that distinct equilibria can exist, given the trigger points and discrete jumps in supply. Here we want to investigate this issue in the context of the numerical model of the EU ETS. As we will see, the calibrated demand function indeed supports three distinct equilibria. One equilibrium has been used in the subsections above (i.e., the calibrated baseline scenario), the others have a slightly higher price path.

When looking into this, it is useful to consider the level of banking at the end of the last period, considering different starting prices producing Hotelling-consistent price paths. The outcome of the exercise is shown in Figure 2.5 for the first-period price interval 20-22 Euro per tCO_2. In equilibrium final banking must equal zero.

At first thought, we would expect net banking to be a monotonically increasing function of the price, as a higher price increases abatement and hence reduces demand for allowances. However, we see from the figure that net banking is only piecemeal increasing in the price, and then drops down at certain price levels. Moreover, we notice that there are three distinct first period prices where net banking at the end of the last period is zero, one at 21.0, one at 21.3, and one at 21.4 Euro per tCO_2 (marked with small circles). In other words, all these three prices (price paths) are feasible equilibria given the calibrated demand function.

When comparing the distinct equilibrium price paths, we observe that these are rather close to one another, suggesting equilibrium multiplicity is not an important problem in terms of magnitude. The minor difference in (initial) prices is somewhat deceptive, though. A slightly higher initial price (e.g. 21.0 vs. 21.3) leads to slightly more banking, which can cause a substantial jump in cumulative cancellation of allowances and therefore emissions. Indeed, cumulative cancellation is close to 200 Mt higher in the equilibrium supported by an initial price of 21.4 Euro per tCO_2 compared to the equilibrium with a starting price of 21.0 Euro per tCO_2. The net decrease in emissions of nearly 200 Mt is roughly equal to Dutch CO2 emissions in 2019, or four times Norway's. We provide a more detailed discussion in Appendix 2.C, where we also show the impacts on cancellation.

2.4 Policy Implications

What are the implications of our results for the design of cap-and-trade schemes? On the one hand, it is intuitively desirable to allow for endogenous cap-adjustments in cap-and-trade schemes – the EU experience with a large oversupply of allowances serves as a good illustration. On the other hand, the present paper establishes that a cap-and-trade scheme with an endogenous cap suffers from a green paradox. What avenues are there to reconcile these two observations?

First, and most intuitively, the system could match any demand-reducing policy with a (sufficient) decrease in the future supply of allowances. This reduction in supply directly avoids the green paradox. Such a solution is not without complications. The MSR was intended to avoid the need for discretionary policy making through manual adjustment of supply. For years, the European Commission had been worried about the steadily increasing bank of unused emissions allowances and understood something had to be done about it. The MSR was introduced as a solution to the perceived over-supply of allowances without the need for ad hoc supply-adjustments and the political difficulties involved. Hence, simply complementing reduced future demand by a reduction in future supply, while an academically proper solution indeed, may well

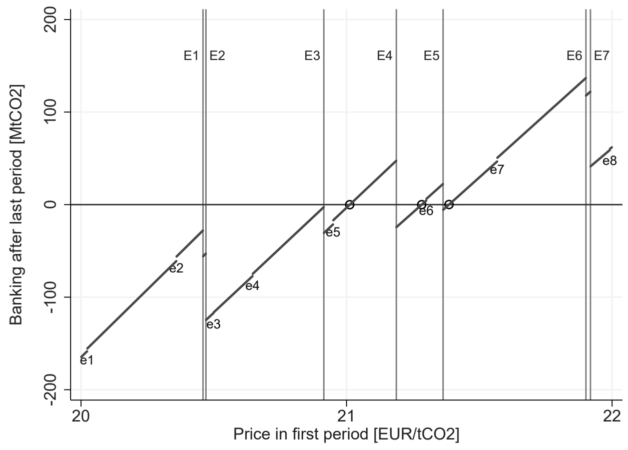

Figure 2.5 – This figure shows banking after the last period as a function of the initial price, and illustrates the multiplicity of equilibria generated by the MSR. By definition, an equilibrium is characterized by the intersection of the banking curves with the horizontal line at 0. In this particular case, three equilibria exist: one at a first-period price of 21.0, the other at a price of 21.3 and 21.4. The seven vertical lines at discrete jumps in the banking function indicate major MSR-events. The eight minor discontinuities labeled by e1-e8 indicate minor MSR-events. More details in Appendix 2.C

be politically difficult. Moreover, the ETS remains sensitive, in the counter-intuitive direction, to expectations about future demand driven by e.g. drifting consumer preferences.

Second, as a more drastic change, the European Commissions might add a price targeting mechanism to the MSR. Revealed preferences of EU policy makers suggest that they are not fond of too low allowance prices, since that makes it obvious that the ETS does not significantly contribute to EU climate policy. On the other hand, they seem to be afraid that tightening the allowance supply "too much" will lead to a carbon price that is unacceptably high for voters and firms in the EU. If those are the basic political economy forces shaping the design of the ETS, how could we make the best of the system?

In a simple price-focused setting, canceling can be triggered when prices fall below a floor price, like in RGGI or as has been proposed for the EU ETS. As discussed in our theoretical model, such discrete events introduce multiplicity and thus unpredictability when the equilibrium comes close to a trigger event. As a fix, one could devise more sophisticated (continuous) rules that implement an upwards sloping 'marginal damage curve' for climate change under uncertainty [53]. Under such a policy, canceling would decrease, and cumulative emissions would rise, continuously with prices. A well-designed hybrid price-quantity policy along those lines prevents the green paradox. A drop in demand, independently of when it occurs and whether or not it is anticipated, lowers the price of allowances and increases canceling. This policy therefore reduces cumulative supply unambiguously. It establishes a negative feedback loop between demand and supply and thereby maintains effectiveness of complementary climate policies. As an additional benefit, it reduces price volatility substantially.

While the above suggestions concern canceling *within* the MSR, a future revision of the ETS must also consider the exchange *between* the market and the MSR, that is, the intake and outflow. We raise two points in this regard. First, we see no clear benefits from discrete jumps, while we do see important disadvantages. We therefore propose a change toward continuous rules rather than moving discrete lumps of allowances in and out of the MSR in response to trigger events. Second, we believe that the flows of allowances between the market and the MSR serve a different purpose than the cancellation rules. Their setups should therefore be guided by a different principle. Cancellation is meant to insure an efficient balance of supply and demand. Subject to our proposed reforms of the MSR, we think the EU ETS would indeed achieve this balance. The flows of allowances, in addition, have an effect on market liquidity. We believe these should also be considered by the policy maker. On the one hand, a large bank of privately held allowances turns price volatility into asset risks.[19] On the other hand, a small bank of privately held allowances causes a collapse of intertemporal trade, which *causes* price volatility. The latter type of induced price volatility is illustrated by experiences in the South Korean ETS. The rules for the flows of allowances between the market and the MSR should thus aim at sufficient but not excessive market liquidity. To try and reach this balance, flows could be made responsive to the ratio between the amount of reserve allowances held by firms versus those surrendered.

In the end, our results may leave one wonder whether the endogenous cap in the EU ETS is a good thing at all. This is an issue regarding the relevant counterfactual of the policy and can be split into two sub-questions. One is whether cancellation through the MSR reduces emissions in general, the other whether the EU ETS interacts properly with other emissions-reducing policies. Our answer to the first of these is affirmative: canceling allowances in the MSR reduces cumulative emissions compared to the functioning of the EU ETS before 2018. The green paradox identified in this paper expressly pertains to the interaction of the EU ETS with other policies intended to bring down emissions. It is those policies that, when interacted with the MSR, may become counterproductive. Future revisions of the EU ETS should therefore pay careful attention to the interaction of the rules for cancellation with other policies.

[19]This is particularly relevant as it adds a layer of firms' interests to future changes in ETS regulation that is not so easy to gauge.

Price-based cancellation rules would make for a useful addition to the ETS toolkit.

2.5 Conclusions

This paper establishes that a cap-and-trade system with an endogenous emissions cap like in the EU ETS suffers from a strong green paradox: cumulative emissions may increase in response to overlapping policies that reduce demand. Our analysis highlights the importance of anticipation: an expected shift in consumer preferences, or currently announced policies aiming to reduce emissions in the future, run the risk of being severely impaired if not more than overturned, whereas surprise policies may still be (somewhat) effective. Our green paradox is even stronger than the one previously pointed to in the economics literature [136].

That pre-announced policies may be less effective than 'surprise' ones is not a new insight, nor is it limited to the case of environmental policy. In fiscal policy, for instance, pre-announcement of policies has been found to substantially decrease their *net* effect [11, 108]. Monetary policy is another such example [134]. Our finding of a strong green paradox only underlines further the importance of carefully considering new policies, including how and when to communicate them, especially so if this communication takes place in advance of actual implementation.

A particular case in point to which our result applies is the European Green Deal. Presented by the European Commission in December 2019, this policy pledges to a 50-55 percent reduction in greenhouse gas emissions by 2030, increasing to 100 percent by 2050. The mechanism highlighted in our paper speaks directly to this proposal: Market participants, anticipating a policy-induced plunge in demand for allowances by 2030, attach less value to allowances beyond then, let alone 2050. Consequently, more allowances will be used today, leading to a reduced bank. This automatically reduces inflow into the MSR, and thus leads to less cancelation. In the coming decade, fewer allowances may be permanently canceled, increasing aggregate ETS emissions as compared to the situation where no Green Deal had been enacted. One can come up with several solutions to this dismal result, as discussed in the previous section.

One crucial assumption behind our analysis is that the market has perfect foresight about the future ETS market. This is a strong assumption, but we believe that the mechanism underlying our result is highly relevant also with imperfect foresight. Still, an important question is to what degree market participants let expectations about the future affect their current decisions [43, 90]. Incorporating different forms of expectations into our model framework would be one interesting avenue for future research.

Acknowledgements

We are grateful for help from two anonymous referees and the editors for their constructive suggestions on the structure of the paper and discussion section. We acknowledge funding from The Research Council of Norway through CREE (grant 209698; Gerlagh and Rosendahl) and the NorENS project (grant 280987; Rosendahl).

2.A Proofs and figure for the two-period model

PROOF OF PROPOSITION 2:

Proof. Totally differentiating the price equation (2.2) gives

$$dp_1 = \psi_1'(de_1 - d\lambda_1), \tag{2.14}$$
$$dp_2 = \psi_2'(de_2 - d\lambda_2). \tag{2.15}$$

We cancel p_1 and p_2 and merge both equations into one, by Hotelling's rule (2.3).

$$(1+r)\psi_1'(de_1 - d\lambda_1) = \psi_2'(de_2 - d\lambda_2). \tag{2.16}$$

Then we substitute e_1 for e_2 through aggregation of the allowances balances (2.5),(2.7) over both periods, and taking differences,

$$de_2 = -(1-\delta')de_1, \tag{2.17}$$

resulting in

$$((1+r)\psi_1' + (1-\delta')\psi_2')de_1 = (1+r)\psi_1' d\lambda_1 - \psi_2' d\lambda_2. \tag{2.18}$$

Together with (2.4),(2.9), this gives the proposition's equations. □

PROOF OF PROPOSITION 3

Proof. Without loss of generality, assume that an equilibrium exists just below the canceling jump, $b = \bar{b} - \varepsilon$, supported by p_1^*, and with cumulative emissions E_1^*. If we slightly raise prices, first-period demand goes down and banking goes up. When $b = \bar{b}$ is reached, aggregate supply drops discretely, by $\delta\bar{b}$, resulting in strict excess demand. We have to further raise prices to find a new equilibrium. With those higher prices, banking in the first period further increases, thus cumulative supply further decreases. This proves that if we find a new equilibrium, it must satisfy $E^* < E^{**} - \delta\bar{b}$. Assuming supply does not become negative with rising prices, a second equilibrium with the stated properties must exist. □

FIGURES SUPPORTING THE TWO-PERIOD MODEL.

For readers interested in a rigorous yet intuitive understanding of the above two proofs of propositions, below we add a graphical representation with emissions in the two periods on the axes. Upwards sloping lines represent demand satisfying Hotelling's rule (2.3). That is, the lines represent demand (e_1, e_2) for a set of possible prices (p_1, p_2) that satisfy $p_2 = (1+r)p_1$. If prices go up, demand in both periods goes down. If prices go down, demand in both periods goes up. Hence the curve is upwards sloping. The downwards sloping lines represent supply as in (2.5)-(2.7). If banking falls short of the threshold, $b < \overline{b}$, so that $e_1 > \overline{s}_1 - \overline{b}$, then cumulative supply is fixed by $\overline{s}_1 + \overline{s}_2$. If banking exceeds the threshold $(e_1 > \overline{s}_1 - \overline{b})$, cumulative supply drops by a discrete amount and decreases with reductions in first-period demand, that is, the slope of the supply curve is decreasing at less than 45 degrees.

In the left panel, the central line of the three demand lines is the benchmark, with no policies, $\lambda_1 = \lambda_2 = 0$. Demand shifts left if demand is reduced in the first period $(\lambda_1 < 0)$, and this reduces cumulative emissions since the supply curve is decreasing at less than 45 degrees. A demand-decreasing policy in the second period, $\lambda_2 < 0$, that is a shift of the demand curve down or to the right, must increase emissions, for the *same* reason: the supply curve is decreasing at less than 45 degrees.

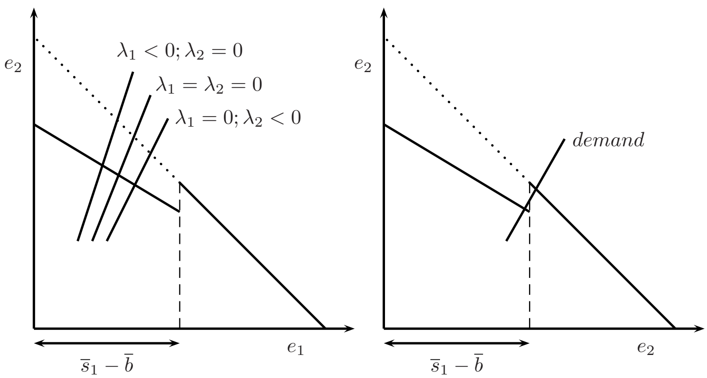

Figure 2.6 – Equilibrium. The left panel presents demand shock dampening and green paradox as in Proposition 2. The right panel shows multiplicity of equilibrium as in Proposition 3. Upwards sloping lines represent demand satisfying Hotelling's rule (2.3). Downwards sloping lines represent supply as in (2.5)-(2.7).

2.B EU ETS model details

2.B.1 Model structure

For our quantitative model of the EU ETS, we consider time periods $t \in \{1, ..., T\}$ and refer to the entire time window if not stated otherwise. We use capitals for stocks at the end of a period (so that a stock at the start of the first period has index 0), and lower case variables for flows. The stock of allowances in the MSR is defined through the following mechanical rule:

$$M_t = \min(\beta s_{t-1}, M_{t-1}) + m_t - n_t, \tag{2.19}$$

where

$$(m_t, n_t) = \begin{cases} (0, \min(M_{t-1}, \Gamma)) & \text{if } B_{t-1} < \underline{B} \\ (0, 0) & \text{if } \underline{B} \leq B_{t-1} < \overline{B} \\ (\alpha B_{t-1}, 0) & \text{if } \overline{B} \leq B_{t-1} \end{cases}, \tag{2.20}$$

with s_t the maximum (exogenous) number of allowances issued in period t, β the share of these auctioned, B_t banking from period t to $t+1$, and m_t and n_t flows into and out of the MSR, respectively. The model can be parameterized to the EU ETS by setting $\beta = 0.57$,[20] $\Gamma = 100$, $\underline{B} = 400$, $\overline{B} = 833$, $\alpha = 0.24$ (0.12 from 2024). If M_t exceeds βs_t, the difference is shaved off, and these allowances are canceled permanently.

Equilibrium is characterized through demand e_t, supply s_t, and flows into and out of the MSR. Excess supply is added to the bank of allowances available for future use B_t.

$$B_t - B_{t-1} = s_t - e_t(p_t; \lambda_t) - m_t + n_t \tag{2.21}$$

As before, the one-dimensional parameter λ_t is a demand shifter, through which we study comparative dynamics. It captures the structure of the economy, also describing changes brought about by climate-oriented or other policies. We keep the same notation as in the general model and normalize the parameter λ_t such that $\partial e_t / \partial \lambda_t = 1$.[21] By means of notation, we will abbreviate $\partial e_t / \partial p_t$ as d'_t, so $d'_t < 0$. We define cumulative emissions as $E = \sum_t e_t$.

As allowances are complementary mostly to fossil fuel use, demand is bound from above and well-defined for zero prices. We also set a finite choke price, where no emissions are profitable anymore (e.g., fossil fuels are replaced by renewables).[22]

[20] This is the approximate share of allowances that are auctioned, according to [124].
[21] We could, for example, specify $D(.) + \lambda_t$ as residual demand, but we like to think of policies in a more generic framework.
[22] The prices at which emissions become unprofitable may not be as excessively high as previously believed, see e.g. Wilson and Staffell [143] and Gillingham and Tsvetanov [59].

Given the above structure, the full EU-ETS model is characterized by the parameters presented below.

2.B.2 Model parametrization

Table 2.1 – Specification of parameter values

Parameter	Description	Value	
$\overline{B}$	Threshold for inflow into MSR	833 Mt	
$\underline{B}$	Threshold for outflow from MSR	400 Mt	
α	Withdrawal rate (pace of inflow into MSR)	0.24	(2019-2023)
		0.12	(after 2024)
Γ	Outflow from MSR	100 Mt	
β	Threshold factor for canceling allowances	0.57	
s_{2019}	Supply of allowances in 2019	1,893 Mt	
	Linear reduction factor of supply per year	-0.0174	(until 2020)
		-0.0220	(after 2020)
B_{2018}	Banking end of 2018	1,654 Mt	
	Size of MSR end of 2018	1,640 Mt	
	First year of cancelation	2023	
a	Maximal demand in first year	1,846 Mt	
b	Demand function slope in first year	8.336 Mt/€	
c	Relative decrease in demand per year	-0.0206	
r	Discount rate	0.05	

Mainly based on data from European Commission (https://ec.europa.edu/climat/policies/ets/reform_en and https://ec.europa.eu/clima/policies/ets/cap_en), [124] and [129].

Table 2.1 displays the specification of parameter values in the model. Several of the parameters are either specified by the policy, or based on historic observations (i.e., emissions and banking). The last four parameters in Table 2.1 are uncertain but important. The main text explains the calibration procedure. Here some more details are provided.

First, for the (real) interest rate, 5 percent is chosen. There are arguments for both higher and lower rates. Looking at futures prices of EUAs suggest a lower interest rate, even in nominal terms.[23] At the time of writing, the annual futures prices increase by 3-4 percent in the period 2020-2025. On the other hand, the future of the EU ETS is uncertain, and recurring regulatory changes enhance the future price uncertainty. This suggests a high market interest rate (or a gradually higher interest rate to reflect

[23]https://www.barchart.com/futures/quotes/CK*0/all-futures

that regulatory uncertainty increases over time, especially between phases).[24]

Next, as mentioned in the main text we require three features to be fulfilled when calibrating the demand function. First, the level of demand (emissions) should be consistent with the observed price and demand combination in 2018. The average EUA price in 2018 was 16.0 Euro per ton. Emissions in 2018 were 1749 Mt.[25]

Second, the simulated Base Case scenario, which includes the MSR rules, should have an initial price in 2019 at 21.0 Euro per ton. This is equal to the average price in the last quarter of 2018 (when adjusting for the interest rate). The EUA price was rising steadily in the three first quarters of 2018, whereas the price trend afterwards has been quite flat (the price has been volatile though).

Third, a simulated scenario that does not include the MSR rules should have an initial price in 2019 at 7.5 Euro per ton. The average price from the start of phase 3 in 2013 to the first half of 2017, i.e., just before the price started to take off, was 5.8 Euro. Adjusting for the (real) interest rate of 5 percent and inflation rate of 1.5 percent, this corresponds to 7.5 Euro in 2019.

As mentioned in the main text, the calibration leads to a choke price of 221.5 Euro per ton and an annual reduction factor for demand of 2.1 percent, which is of the same size as the reduction factor the EU applies for supply.

More generally, it is difficult to know how price responsive demand is, and it is hard to foresee how the demand function will change over time. On the one hand, economic growth tends to push the demand upwards. On the other hand, technological progress and supplementary policies related to renewables, energy efficiency and coal phase-out, tend to push the demand downwards. The calibration might suggest that market participants in aggregate believe the latter to be dominating the former.

As explained in the main text, the end year of the EU ETS follows from the calibration, and turns out to be 2066.

Regarding the initial size of banking and MSR, 1 654 million allowances were banked in the market from 2018.[26] 900 million allowances were "back-loaded" in 2014-16, which means that auctioning of these allowances was postponed (implicitly banked by the regulator). Eventually, it has been decided that they should enter into the MSR, together with expectedly 740 million allowances ([129]).

---

[24] An alternative approach could be to assume (partly) myopic behaviour by the market participants.
[25] https://ec.europa.eu/clima/news/emissions-trading-emissions-have-decreased-39-2018_en
[26] https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2019_3288_en.pdf

2.C Multiplicity of equilibria

What are the details behind the multiplicity of equilibria in Section 2.3.5? It is useful to first consider the drop in net banking at the price of 21.2 (Event 4 (E4) in Figures 2.5 and 2.7). When the initial price is around 21.2, the level of banking falls below the threshold of 833 Mt in 2048. Hence, no more allowances enter into the MSR the following year. If the initial price is below 21.2, banking never exceeds the threshold again. However, if the initial price is 21.2, banking rises slightly above the threshold once more in 2049. Hence, 100 Mt ($0.12 * 833$) more allowances enter into the MSR (instead of being auctioned) compared to the case where the initial price is just below 21.2, and thus fewer allowances are available in the market. Net banking at the end of the last period is therefore lower even though the price path is (marginally) higher.

As the size of the MSR increases by 100 Mt in 2050 when the initial price is 21.2, but not if it is just below 21.2, it follows that 100 Mt more allowances are (not) shaved off if the initial price is equal to (just below) 21.2. In Figure 2.7, we see indeed that cumulative cancellation jumps considerably around the initial price of 21.2, but not as much as 100 Mt. The reason is that the other MSR threshold also plays a role here, i.e., when allowances should return to the market (400 Mt). If the initial price is just below 21.2, banking in 2057 is above the threshold, while if the price is 21.2, banking is below the threshold. Only in the latter case are allowances released from the MSR the following year, in which case there is no more cancellation. In the former case, the size of the MSR is somewhat above the cancellation threshold, and 28 Mt more allowances are canceled before the threshold is passed the year after. This mitigates to some degree what happens in 2049, and so the net difference in cancellation is 72 Mt ($100 - 28$).

A similar story explains the drop in net banking when the initial price is around 20.5 (Event 2) or 21.9 (Event 7), that is, there is one more year of inflow into the MSR when the initial price is marginally above the stated price compared to when it is marginally below (the 400 Mt threshold also plays a role in these cases). For the other and smaller drops in net banking in Figure 2.5 (E1, E3, E5 and E6), only the outflow threshold plays a role.[27]

[27] The figures also show eight minor events: small jumps up and down in banking and cancellation, respectively (e1-e8). In these cases, banking first drops below the 833 Mt threshold and then rises above the threshold again one or two years later, lasting only one year implying one more year of inflow into the MSR. If the price is marginally *above* e.g. the e1 price, banking is *marginally* above the threshold *one* year later, while if the price is marginally *below* the e1 price, banking is *significantly* above the threshold *two* years later. Hence, there is more inflow and subsequent cancellation in the latter case. Note than in the simulations in Sections 2.3.4-2.3.5 there is no such "pause" in the inflow into the MSR.

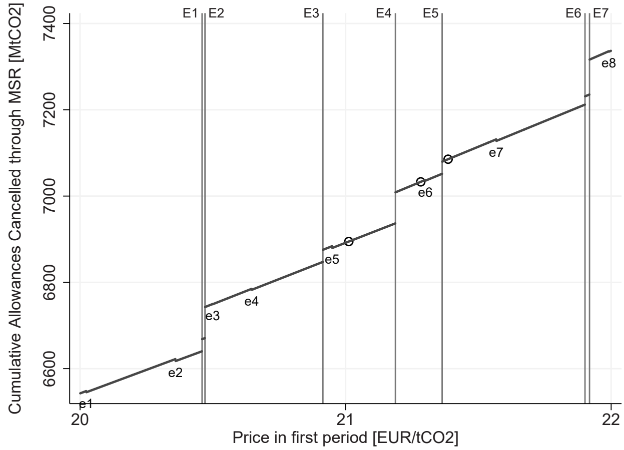

Figure 2.7 – This figure shows the cumulative cancellation of allowances as a function of the initial price, and relates to Figure 2.5. Whenever one of the MSR thresholds is passed, cumulative cancellation shifts up or down.

2.D GAMS Program

```
Sets

* EU ETS is simulated for the years 2019-2067. t=0 is 2018, so t=49 is 2067. Both
demand and supply are zero from year 2067 according to the calibration.

t Time period /0*49/

t0(t) Period t=0 (before simulation starts)

ts(t) Simulation periods

ts2(t) Simulation periods except t=1

tn(t) Last period

;


alias(t,tt);

alias(t,ttt);


t0(t) = yes$(ord(t) eq 1) ;

ts(t) = yes$(ord(t) gt 1) ;

ts2(t) = yes$(ord(t) gt 1 and ord(t) lt card(t)) ;
```

```
tn(t) = yes$(ord(t) eq card(t)) ;

Scalars
r Discount rate
beta Threshold for canceling allowances (as a share of s)
p0 Average price in 2018 (t=0)
d0 Demand in 2018 (t=0)
apar Parameter a in demand function
bpar Parameter b in demand function
cpar Parameter c in demand function
;

r = 0.05 ;
* Assumed share of auctioning
beta = 0.57 ;
* Average price in 2018 used to calibrate demand function
p0 = 16 ;
* Demand (incl aviation) in 2018
d0 = 1749 ;
bpar = 1/0.1175 ;
apar = (d0 + p0*bpar) ;
cpar = -0.020566 ;

Parameters
s(t) Fixed allocation of quotas
alpha(t) Withdrawal rate - share of annual auction volume entering into MSR
deltaD(t) Reduced demand for quotas in year t
;

* Supply (incl aviation) from 2019 based on https://ec.europa.eu/clima/policies/ets/cap_en
s(t)$(ord(t) le 3) = 1931 - (ord(t)-1)*38.264;
s(t)$(ord(t) gt 3) = s("2") - (ord(t)-3)*49.216;
```

```
alpha(t)$(ord(t) le 6) = 0.24 ;
alpha(t)$(ord(t) gt 6) = 0.12 ;
deltaD(t) = 0 ;

Positive Variables
p(t) Price
d(t) Demand for quotas
CumD Cumulative demand for quotas
m_in(t) Number of quotas entering into MSR
m_out(t) Number of quotas taken out of MSR and into the ETS market
M(t) Size of MSR
C(t) Cancellation of quotas
CumC Cumulative cancellation of quotas
;

Variables
B(t) Banking of quotas
;

Equations
EQ1(t) Quotas entering into MSR
EQ2(t) Quotas taken out of MSR
EQ3(t) Cancellation of quotas
EQ4(t) MSR stock change
EQ5(t) Market balance
EQ6(t) Price movement
EQ7(t) Demand for quotas

* The following equations sum up cumulative cancellation and demand:
EQ3SUM Cumulative cancellation of quotas
EQ7SUM Cumulative demand for quotas
```

* The following equation is used in the model without MSR:

EQ3NO(t) Without cancellation of quotas from MSR

;

* Due to the discontinuity of the m_in function, the formulation is somewhat different from the equation in the paper,

* and a marginal number is added to the denominator to avoid division by zero

EQ1(t)$(ts(t)).. m_in(t) =E= MAX(0 , alpha(t)*B(t-1)*(B(t-1) - 833))*(B(t-1) - 833) / ((B(t-1) - 833)*(B(t-1) - 833) + 0.01) ;

* Due to the discontinuity of the m_out function, the formulation is somewhat different from eq.2 in the paper,

* and a marginal number is added to the denominator to avoid division by zero

EQ2(t)$(ts(t)).. m_out(t) =E= MIN(M(t-1),(MAX(0 , 100*(400 - B(t-1)))*(400 - B(t-1)) / ((400 - B(t-1))*(400 - B(t-1)) + 0.01))) ;

EQ3(t)$(ord(t) gt 4).. C(t) =E= MAX(0 , M(t) - beta*s(t)) ;

EQ4(t)$(ts(t)).. M(t) =E= M(t-1) + m_in(t) - m_out(t) - C(t-1);

EQ5(t)$(ts(t)).. s(t) - m_in(t) + m_out(t) =E= d(t) + B(t) - B(t-1) ;

EQ6(t)$(ts2(t)).. p(t+1) =E= p(t)*(1+r) ;

EQ7(t)$(ts(t)).. d(t) =E= (apar - bpar*p(t))*(1 + cpar*(ord(t)-1)) - deltaD(t) ;

EQ3NO(t).. C(t) =E= 0 ;

EQ3SUM.. CumC =E= sum(t,C(t)) ;

EQ7SUM.. CumD =E= sum(t,d(t)) ;

* Main model with MSR: Model MSR_YES /EQ1.m_in, EQ2.m_out, EQ3.C, EQ4.M, EQ5.p, EQ6.B, EQ7.d, EQ3SUM.CumC, EQ7SUM.CumD /;

```
* Model without MSR: Model MSR_NO /EQ1.m_in, EQ2.m_out, EQ3NO.C, EQ4.M,
EQ5.p, EQ6.B, EQ7.d, EQ3SUM.CumC, EQ7SUM.CumD /;

* Model to help GAMS find solution, with fixed price and endogenous banking last
period Model MSR_EX /EQ1.m_in, EQ2.m_out, EQ3.C, EQ4.M, EQ5.B, EQ7.d,
EQ3SUM.CumC, EQ7SUM.CumD / ;

* The initial value of MSR and B:
M.fx("0") = 900 + 740 ;
B.fx("0") = 1654 ;

* Fixing variables in period 0 (2018):
m_in.fx("0") = 0 ;
m_out.fx("0") = 0 ;
d.fx("0") = 0 ;
C.fx(t)$(ord(t) le 4) = 0 ;

* Last period requirements:
M.fx(t)$tn(t) = 0 ;
B.fx(t)$(ord(t) eq card(t)) = 0 ;

* Ensure that prices must be strictly positive:
p.lo(t) = 0.1 ;

option iterlim=100000000;
option reslim=2000.0;
option limrow=10;

*Help GAMS find the wanted equilibrium (due to multiple equilibria)
P.fx(t) = 20.5*(1+0.5*r)*(1+r)**(ord(t)-2);

Solve MSR_EX using mcp;

* Then relax prices and require last period banking to be zero
```

```
P.lo(t) = 0.1 ;
P.up(t) = inf ;
B.fx(t)$(ord(t) eq card(t)) = 0 ;
* Solve the model including MSR: Solve MSR_YES using mcp;

******************************
* Without MSR (and backloading)
alpha(t) = 0 ;
B.fx("0") = B.l("0") + M.l("0");
M.fx("0") = 0 ;

* Solve the model excluding MSR:
Solve MSR_NO using mcp;
```

CHAPTER 3

Linking Cap And Trade Schemes

3.1 Introduction

The number of cap and trade schemes to mitigate greenhouse gas emissions has grown steadily.[1] Reduced to its core, a cap and trade scheme caps CO_2 emissions by allocating allowances to emitters who are then allowed to trade their permits; if a firm emits CO_2, it must surrender an equivalent amount of allowances. The policy combines a conservative certainty on emissions offered by direct command-and-control measures with an efficient allocation of abatement efforts realized through a carbon tax.

Cap and trade schemes can link. A linkage between two schemes reciprocally enables the use of permits issued in one scheme to meet compliance obligations pursuant to another. Linking is seen as a promising development in cap and trade regulation [107]. Article 6 of the Paris Agreement expressly provides for the possibility of linking. Linking has become increasingly prominent in recent years. California's cap and trade system linked with Quebec's on 1 January 2014 and the schemes organize joint auctions. On 1 January 2020, a link between the European Union's Emissions Trading System (EU ETS) and the Swiss Emisions Trading System came into force. Linkages between the Regional Greenhouse Gas Initiative (RGGI) and the Emissions Trading Systems of Virginia and Pennsylvania are currently on their way, as are implicit linkages between California's ETS and Washintong State's Clean Air Rule.[2]

Linking is efficient because it leads to an equalization of marginal abatement costs across jurisdictions. An additional benefit may be that, through their increased cooperation, local planners are less likely to choose their policies noncooperatively

[1] The first major emissions trading system (ETS) for greenhouse gases – the European Emissions Trading System (EU ETS) – was established in 2005. To date, there are 20 ETSs in place across five continents and covering 27 jurisdictions which produce almost 40 % of global wealth (GDP). With over a dozen more governments considering or having already scheduled an ETS, emissions trading has emerged as a key instrument to cost effectively decarbonize our economies. [83]

[2] The latter link is mostly hypothetical at this point, as Washinton State's Clean Air Rule was suspended after a 2018 court ruling. Though contested, the ruling was largely upheld by the Washington State Supreme Court on Jan. 16, 2020.

[109], leading to a more efficient total emission levels.

This paper proposes a theory of optimal linking under abatement cost uncertainty. Linking two trading systems means that a firm can fulfill compliance obligations pursuant to one jurisdiction by means of emission allowances issued by the other. In practice this means that polluters in either jurisdiction are allowed to trade emission allowances freely and on a one-to-one basis. Free inter-scheme trade of allowances ensures that firms equate marginal abatement costs both within and across schemes. This is necessary for an optimal linkage because as long as marginal abatement costs are not equal across jurisdictions, mutually beneficial exchanges of allowances can be made, contradicting the notion of efficiency. The intuition is essentially the same as that favoring cap and trade over more direct command and control policies in a single jurisdiction. The literature on linking has often emphasized this channel of potential efficiency gains [30, 38, 39, 48, 78, 107].

In addition to marginal abatement cost equalization, an optimal linkage exploits a second channel to boost the performance of the linked schemes: learning. Allowances are traded between the schemes when marginal abatement costs differ across jurisdictions. The number of allowances traded between the schemes thus provides a sufficient statistic for the gap in marginal abatement costs under the initial allocation. Knowledge of this gap allows the planners to learn something about realized abatement costs in both jurisdictions. Since this posterior will generally be different from their prior, the planners thus learn that the initial allocation of emission allowances was inefficient for two reasons. First, the distribution of allowances between the schemes, given the global cap, was suboptimal. This inefficiency is dealt with through trading. But second, the cap itself may turn out ex post inefficient from the point of view of global welfare. An optimal linkage attempts to deal with both of these inefficiencies.

To see how a flow of allowances between jurisdictions signals in inefficient global cap, note that the level of the ideal cap balances the cost of climate change and the cost of abatement. When posterior beliefs about abatement costs deviate from planners' expectations, that balance is lost. In this sense, emission levels are ex post inefficient and the planners know it, not because they possess perfect information, but because they update their beliefs based on net trade between the schemes. We therefore propose to adjust the global cap in response to trade between the jurisdictions. To our knowledge, we are the first to study such endogenous cap adjustments in the context of linked cap and trade schemes.

Interestingly, what drives cap adjustments is not the amount of uncertainty per se, but rather the degree to which uncertainty is asymmetric between jurisdictions. This has a clear intuition. Trade flows signal a wedge in jurisdictional marginal abatement costs. Learning about the *absolute* level of abatement costs occurs when planners update beliefs, mostly for the least predictable jurisdiction. Updating, in turn, is done by anchoring beliefs about the least predictable jurisdiction on beliefs about the most predictable one. In the extreme case where the planners are uncertain about abatement costs in one jurisdiction only, trade flows allow them to pin down abatement costs in the uncertain jurisdiction exactly. Since in this case there is de facto complete information about abatement costs, the planners are able to implement the first-best social optimum. That is, by smartly linking emission trading schemes, aggregate uncertainty can be reduced to match the least uncertain scheme.

Indeed, optimal linking deviates from emissions traded one-for-one (or, in terms of climate change, ton-for-ton), when jurisdictions have asymmetric uncertainty [76]. But the efficiency gain associated with cap flexibility comes with a substantial loss of allocative efficiency. To illustrate, suppose we were to contemplate an exchange rate such that 1 allowance issued by jurisdiction N can be traded against 2 allowances issued in jurisdiction S. Then firms in N and S will trade allowances until the marginal cost of reducing emissions in N equals *half* the marginal cost of reducing emissions in S. A non-unitary exchange rate thus drives firms' incentives away from an efficient distribution of abatement efforts.[3]

Cap adjustments based on observed allowance prices is another alternative policy. Compared to quantities, prices are highly efficient information aggregators. Indeed, when the planners observe both emissions and the market price for allowances, they can perfectly back out the abatement cost functions in both jurisdictions. The possibility of using price information hence allows for implementation of the unconstrained best cap on emissions. Our first and foremost recommendation is therefore to adjust the caps in response to carbon prices. Importantly, in practice proposed price-based interventions are often discrete and based on price thresholds; the implementation then remains imperfect and our quantity-based optimal linkage can perform better as it allows for a continuous processing of market information.[4]

Linking cap and trade systems across jurisdictions is related to integrating cap and trade markets over time [144]. Dynamic linking was studied in [71] and [128] for flow pollutants, and in [53] for stock pollutants.[5]

Although we use the language of multiple cap and trade schemes, our analysis also applies to situations where a previously uncovered industry is newly added to an

[3]The same need not apply to local pollutants like NO_X or lead pollution.

[4]An important example to which our theory applies is any linkage involving the EU ETS. Despite repeated calls for a European price floor [49], the European Union uses only information on quantities for cap-adjustments. Linkages between any cap and trade scheme and the EU ETS will hence benefit from our analysis, "key features for compatibility for linking" being "complications around intervention in price" (EU Commission, 2015, EU ETS Handbook)."

[5]For EU ETS, [55] and [57] illustrate several unexpected side-effects of endogenous intertemporal emission caps. This offers an important warning: endogenous cap-adjustments can be efficient, but details matter.

existing scheme, or to cases where multiple unregulated industries are combined into a newly formed cap and trade scheme. Our results are therefore relevant in discussions on such topics as the inclusion of road transport among the industries covered by the EU ETS, or on the extension of RGGI beyond the electricity sector. Similarly, our analysis motivates the question whether clearly identifiable jurisdictions within existing schemes – member states in the EU ETS, or states in RGGI – are currently "linked" in the most efficient way possible. These are highly relevant policy questions that deserve greater attention from policymakers and academics alike.

The paper is organized as follows. Section 3.2 introduces our model and the building blocks for welfare analysis. Section 3.3 discusses different types of (integrated) cap and trade policies and develops our theory of optimal linking. At the end, we revisit the perennial question of instrument choice, prices versus quantities [140]. Section 3.4 concludes. Proofs and lengthy derivations are in the Appendix.

3.2 Model

Given are two jurisdictions, North and South, each operating its own cap and trade scheme. The assumption of two jurisdictions is not restrictive. One may simply consider North a representative jurisdiction for two linked jurisdictions, East and West, where trade between North and South is essentially a reduced-form way of writing trade between East, West, and South. The term jurisdiction, too, should not be narrowly interpreted.

Each jurisdiction i is populated by firms that produce a composite good the production of which causes emissions. We may write benefits $B_i(\tilde{e}_i; \theta_i)$ as a function of emissions $\tilde{e}_i$, given by:

$$B_i(\tilde{e}_i \mid \theta_i) = (p^* + \theta_i)(\tilde{e}_i - e_i^*) - \frac{b_i}{2}(\tilde{e}_i - e_i^*)^2. \tag{3.1}$$

Emissions yield benefits because they allow firms to produce goods and save on the cost of abatement. As an umbrella term, we refer to $B_i(\tilde{e}_i \mid \theta_i)$ as abatement costs in jurisdiction i, but other interpretations are possible. For notational convenience, we normalize benefits relative to the ex-ante optimal allocation e_i^* and prices $p_i = p^*$. The parameter θ_i is a fundamental of jurisdiction i's economy and is *private information* of its constituent firms, though it is common knowledge that $\mathbb{E}[\theta_i] = 0$, $\mathbb{E}[\theta_i^2] = \sigma_i^2$, and $\mathbb{E}[\theta_N \theta_S] = \rho\sigma_N\sigma_S$. One way to think about this parameter and the fact that it is unobserved by the policymakers is in terms of uncertainty in the (residual) demand for emission allowances [23]. The variance σ_i^2 is a measure for the uncertainty about jurisdiction i's economy. We say that uncertainty is asymmetric if $\sigma_N \neq \sigma_S$.

Emissions accumulate in the atmosphere and cause climate change as a global externality. The cost of climate change is given by:

$$C(\tilde{e}_N + \tilde{e}_S) = p^*(\tilde{e}_N + \tilde{e}_S - e_N^* - e_S^*) + \frac{c}{2}(\tilde{e}_N + \tilde{e}_S - e_N^* - e_S^*)^2. \tag{3.2}$$

Costs are also measured relative to the ex-ante optimum e_i^*. We make the simplifying assumption that emissions have local benefits but global costs. One could imagine more complicated settings where emissions also have strictly regional costs like local air pollution [10, 29]. We abstract from these aspects and focus on the optimal linking of cap and trade schemes to regulate a global externality.

Subtracting the costs of climate change from the benefits due to emissions yields welfare:

$$W = B_N(\tilde{e}_N \mid \theta_N) + B_S(\tilde{e}_S \mid \theta_S) - C(\tilde{e}_N + \tilde{e}_S). \tag{3.3}$$

Policies are set to align polluters' incentives with the global social cost of carbon [93]. We interpret optimal linking as the integrated policy for e.g. an international climate treaty like the Paris Agreement or its successor. Yet even strictly local planners may more or less explicitly consider global climate damages when deciding on mitigation policies. There are at least two pieces of suggestive evidence to support our claim. First, most if not all existing cap and trade schemes are policymakers' attempts at meeting mitigation obligations implied by the Paris Agreement. Since the Paris Agreement is global in scope and intention, cap and trade schemes set up to satisfy the associated pledges explicitly or implicitly operate with a measure of global climate welfare in mind.[6] Second, actual linkages often start from a certain amount of cooperation and mutual agreement on the cap. Indeed, among the "essential criteria" to ensure "compatibility between the systems" mentioned up in Annex I of the *Agreement between the European Union and the Swiss Confederation on the linking of their greenhouse gas emissions trading systems* are the "ambition and stringency of the cap". Similarly, the independent but linked cap and trade schemes of California and Quebec organize joint auctions of allowances, implying a high degree of cooperation in determining the linked caps.

The timing of the game is as follows:

1. The planner of each jurisdiction chooses its local cap;

[6] As an example, "[...] the [European] Commission proposed in September 2020 to raise the 2030 greenhouse gas emission reduction target, including emissions and removals, to at least 55% compared to 1990. [...] This will enable the EU to move towards a climate-neutral economy and implement its commitments under the Paris Agreement by updating its Nationally Determined Contribution." Moreover, "[t]o achieve the EU's overall greenhouse gas emissions reduction target for 2030, the sectors covered by the EU ETS must reduce their emissions by 43% compared to 2005 levels." Retrieved from https://ec.europa.eu/clima/policies/strategies/2030_en.

2. Firms in each jurisdiction i observe their benefit curve (θ_i) and choose their emissions subject to the local cap and whether or not schemes are linked;

3. The planners observe the number of allowances surrendered in each jurisdiction and, depending on the type of policy in place, may buy back or sell additional allowances;

4. Emissions are realized and the game ends.

Observe that our game has one period and is static in that sense. However, within this one period decisions are taken in order so that we essentially study a dynamic framework that is not repeated. We also assume that that between the moment firms observe their benefit functions and the time the game ends, there are no further innovations in the fundamentals θ_i; that is, we study periods of a duration short enough to focus only on the asymmetric information problem without worrying about future uncertainty.

We write $e_i = \tilde{e}_i - e_i^*$ the deviation in emission levels from the ex-ante optimum; similarly we denote $p_i = \tilde{p}_i - p_i^*$. We let $\Delta e := \tilde{e} - e^{SO}$ be the difference between the value of e and its ex post (after observing θ_i) socially optimal value (see subsection 3.2.1). For total emissions, we write $\tilde{E} = \tilde{e}_N + \tilde{e}_S$ and for deviations from the ex-ante optimum $E = e_N + e_S$. We use superscripts for policy rules or scenarios.

Firms are profit maximizers. Once a policy k caps emissions at the level e_i^k, individual firms trade allowances until marginal abatement costs for all are equal to:

$$p_i^k = -b_i e_i^k + \theta_i, \tag{3.4}$$

which is firms' inverse demand for allowances. In a competitive market for allowances, the price at which permits are traded will be p_i^k in equilibrium.

3.2.1 Global Social Optimum

In a perfect world not plagued by an asymmetric information problem − the Social Optimum − a welfare-maximizing planner allocates emissions in each jurisdiction $i = N, S$ so that they satisfy:

$$\frac{\partial W}{\partial \tilde{e}_i} = \underbrace{\frac{\partial B_i(\tilde{e}_i \mid \theta_i)}{\partial \tilde{e}_i}}_{MB_i} + \underbrace{\frac{\partial B_i(\tilde{e}_j \mid \theta_j)}{\partial \tilde{e}_i}}_{0} - \underbrace{\frac{\partial C(\tilde{e}_i + \tilde{e}_j)}{\partial \tilde{e}_i}}_{MC} = 0, \tag{3.5}$$

where $j \neq i$ denotes the jurisdiction that is not i. Equation (3.5) immediately implies that marginal emission benefits should be equal across jurisdictions in an efficient allocation. Since both jurisdictions by assumption operate a cap and trade scheme, marginal benefits of emissions are also equal to the carbon price, so $p_N^{SO} = p_S^{SO} =$

$p^{SO} = MB^{SO}$. Next, since the level of emissions if efficient if and only if marginal climate costs equal marginal benefits in either jurisdiction, we obtain the following conditions for the socially optimal emission levels:

$$c \cdot (e_N^{SO} + e_S^{SO}) = p^{SO} = -b_i e_i^{SO} + \theta_i. \tag{3.6}$$

Equation (3.6) characterizes the Social Optimum and represents three equalities in three unknowns: e_N^{SO}, e_S^{SO}, and p^{SO}. Solving for these, we obtain:

$$p^{SO} = \frac{c(b_S\theta_N + b_N\theta_S)}{cb_N + cb_S + b_N b_S}, \tag{3.7}$$
$$e_i^{SO} = \frac{b_{-i}\theta_i + c(\theta_i - \theta_{-i})}{cb_N + cb_S + b_N b_S}, \tag{3.8}$$
$$E^{SO} = \frac{b_S\theta_N + b_N\theta_S}{cb_N + cb_S + b_N b_S}, \tag{3.9}$$

where $i = N, S$ and $-i$ refers to "the other jurisdiction that is not i". As is intuitive, socially optimal emission levels are higher when abatement is more expensive; E^{SO} increases in θ_i. This basic observation will be useful later on, when we illustrate that trades of allowances between (linked) schemes signal private information about abatement costs to the planners. An optimal linkage exploits this information by adjusting the global cap in response.

For future reference, we note that the variance of prices is given by:

$$\mathbb{E}\left[\left[p^{SO}\right]^2\right] = \left(\frac{c}{c \cdot b_N + c \cdot b_S + b_N b_S}\right)^2 \left[b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S \rho\sigma_N\sigma_S\right]. \tag{3.10}$$

Thus, abatement cost uncertainty translates into price volatility. We will return to this later.

3.2.2 Welfare Losses

We rank policies according to their expected welfare levels. Suppose a policy k induces emission levels $\tilde{e}_i^k$ in jurisdiction i. From firms' equilibrium behavior (3.4), we see that deviations in emissions from the social optimum scale with prices:

$$\Delta^k p_i = -b_i \Delta^k e_i. \tag{3.11}$$

Expected welfare losses relative to the social optimum are then given by:

$$\begin{aligned} L^k &= \mathbb{E}\left[\Delta^k B_N + \Delta^k B_S - \Delta^k C\right] \\ &= \frac{c}{2}\mathbb{E}\left[\left(\Delta^k E\right)^2\right] + \sum_i \frac{b_i}{2}\mathbb{E}\left[\left(\Delta^k e_i\right)^2\right]. \end{aligned} \tag{3.12}$$

Throughout the analysis, we interpret a policy as the implementation of a constrained expected welfare maximization problem. We note that the level of welfare in the Social Optimum, W^{SO}, is hypothetical and unaffected by the policy implemented. Thus, expected welfare maximization subject to a set of policy constraints can be treated as the dual problem of expected welfare loss minimization relative to the Social Optimum, subject to the same constraints. Given the equivalence between these two approaches, we may use them interchangeably for convenience.

Equation (3.12) shows that there are essentially two sources of welfare losses. One derives from an inefficiently high or low level of global emissions; this relates to the balance between the benefit of emissions and the cost of climate change. The second derives from an inefficient distribution of emissions given a global cap; this relates to the balance between the benefit of emissions in each jurisdiction. Conditional on any level of the global cap, whether efficient or not, welfare W is maximized if and only if

$$\frac{\partial W}{\partial \tilde{e}_i} = \frac{\partial W}{\partial \tilde{e}_j}, \tag{3.13}$$

for $i, j = N, S$ and $i \neq j$. Equation (3.13) implies that given any level of aggregate emissions, global welfare can be increased whenever marginal emission benefits are not equal across jurisdictions. If a policy leads to marginal benefit equalization, it guarantees that the resulting allocation of emission levels is at least second-best: it yields the highest level of global welfare given a (possible inefficient) global cap on emissions.

Linking policies as we study here exhibit equal prices across jurisdictions in equilibrium, as we shall explain below. By (3.11), emissions (both local and global) under such policies can therefore be expressed in terms of the common price gap Δp. Plugging this into (3.12), expected welfare losses from a policy featuring equal prices across jurisdictions can be written as:

$$L^k = \frac{1}{2}\frac{(cb_N + cb_S + b_N b_S)(b_N + b_S)}{b_N^2 b_S^2}\mathbb{E}\left[\left(\Delta^k p\right)^2\right]. \tag{3.14}$$

3.3 Policies

3.3.1 Regional cap and trade

The simplest policy operates two separate cap and trade schemes. In this case, the planner of jurisdiction i sets a cap e_i to maximize (3.3). The first-order condition this policy should implement equates expected marginal benefits in each scheme to marginal climate damages. Thus, emissions e_i are set such that

$$\mathbb{E}[MB_i \mid e_i] = MC, \tag{3.15}$$

resulting in emission levels capped at the ex-ante optimum $e_N = e_S = 0$. Plugging these, through (3.8)-(3.9), into (3.12), we obtain expected welfare losses when both jurisdictions operate a regional cap and trade scheme:

$$L^R = \frac{1}{2}\frac{(c+b_S)\sigma_N^2 + (c+b_N)\sigma_S^2 - 2c\rho\sigma_N\sigma_S}{cb_N + cb_S + b_Nb_S}. \tag{3.16}$$

We note that the marginal damages (the RHS of (3.15)) are perfectly known when caps are set, whereas marginal abatement costs are stochastic variables due to the unobserved fundamentals θ_i. Thus, regional cap and trade implements socially optimal emission levels if and only if abatement costs turn out exactly as expected ($\theta_N = \theta_S = 0$). If abatement costs deviate from expectations, regional cap and trade is inefficient for two reasons. First, the allocation of abatement efforts between the jurisdictions may be ex post inefficient (abatement costs may differ between them). Second, the level of emissions is ex post inefficient. The first of these is remedied by linking schemes across jurisdictions.

3.3.2 Linking

When North and South link their cap and trade schemes, each planner sets the expected optimal cap for its jurisdiction but allowances issued in one scheme may be used to fulfill abatement obligations pursuant to another. Thus polluters are free to trade their allowances as long as global emissions are not affected:

$$e_N + e_S = E = 0. \tag{3.17}$$

Linking has attracted a lot of attention in recent years [38, 39, 78, 107]. Just as trade in emission allowances between firms within a jurisdiction is an efficient way to achieve a given amount of local abatement, so the trade of allowances between jurisdictions is an efficient way to achieve a pre-determined amount of global abatement. The intuition is essentially the same: while linking does not affect global emissions, and therefore climatic damages, it does lead to a closer alignment of the benefits and costs of abatement across jurisdictions. In fact, as long as marginal abatement costs in the jurisdictions are *not* the same, firms can and will profitably exchange permits. The integrated market for emission allowances therefore reaches equilibrium only once the price of an allowance is the same in North and South:

$$p_N = p_S. \tag{3.18}$$

Moreover, since a firm in either jurisdiction is willing to sell (buy) an allowance against the going market price as long as the price is above (below) its private marginal abatement cost, marginal benefits are also the same across firms and jurisdictions when schemes are linked:

$$-b_N e_N^L + \theta_N = -b_S e_S^L + \theta_S, \tag{3.19}$$

where e_N and e_S are chosen by the firms conditional on θ_N and θ_S, subject to (3.17). Plugging this into our welfare loss-function (3.12), we obtain:

$$L^L = \frac{1}{2}\frac{1}{b_N + b_S}\frac{b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S \rho\sigma_N\sigma_S}{cb_N + cb_S + b_N b_S}. \tag{3.20}$$

Comparing welfare losses, we can now formally state our first substantive result.[7]

Proposition 4. *Linking cap and trade schemes increases global welfare.*

In contrast to regional cap and trade, linking guarantees that marginal abatement costs are equal in both jurisdictions. For this reason, linking is always weakly better for welfare than regional cap and trade. The planners' problem consists of two steps, each with its own an intuitive meaning. First, the planners of North and South cap local emissions at levels that, in expectations, maximize global welfare. When the local caps are set, allowances can be traded on a one-to-one basis between schemes, as long as emissions overall remain fixed at the sum of the two jurisdictional caps. By linking their schemes, the planners of North and South effectively delay the determination of local emission caps until after θ_N and θ_S are known, guaranteeing an ex post efficiency gain through marginal abatement cost equalization

$$MB = MB_N = MB_S \tag{3.21}$$

In expectations these equal marginal damages. Cumulative emissions $e_N + e_S$ are chosen such that:

$$MB = MB_N = MB_S \tag{3.22}$$
$$\mathbb{E}[MB \mid e_N + e_S] = MC. \tag{3.23}$$

Linking benefits global welfare (Proposition 4) but the effects on individual jurisdictions are ambiguous. To see this, note that prices in equilibrium equate marginal benefits, so that the volatility of prices is equal to the volatility of marginal benefits. Hence if abatement costs in South are much less predictable than in North, $\sigma_S > \sigma_N$, North may import part of the price volatility to which South is subject. If this effect is strong enough, North may be harmed by its linkage with South [64, 78].

Linking suffers from another, more implicit type of inefficiency. Suppose that after trading the planners observe emissions levels e_N^L and e_S^L in jurisdictions N and S, respectively. Since firms will trade allowances between the jurisdictions until marginal abatement costs are equal everywhere, we know that (3.19) must be satisfied under the observed emission levels e_N^L and e_S^L. Rewriting (3.19), the planners therefore learn $\mu = \theta_N - \theta_S$. Conditional on μ, planners update their beliefs on the true marginal abatement cost curve in both of the jurisdictions. Since this posterior will generally deviate from their priors, the expected optimal cap on emissions should ideally respond to the observed trade of allowances. It does not under standard linking.

[7] See appendix for derivations and proof.

3.3.3 Optimal Linking

We will now construct our optimal linking policy. We proceed in two steps. First, we derive the expected optimal emission level conditional on the trade flows between the jurisdictions. Second, we formulate a mechanism that is known to all firms and allows the planners to implement the expected optimal cap for any observed trade of allowances.

As we discussed, when post-trading emissions levels are e_N and e_S in jurisdictions N and S, respectively, the planners can back out μ, the vertical distance between regional marginal abatement cost functions:

$$\mu := b_N e_N - b_S e_S = \theta_N - \theta_S. \tag{3.24}$$

A key observation is that μ contains more information than the relative position of jurisdictions' abatement cost functions alone – it also signals something about the *absolute* location of the curves. To see this most simply, suppose that the planners are uncertain only about θ_N whereas θ_S is perfectly known (i.e. suppose that $\sigma_S = 0$). In this hypothetical case, observing μ is clearly equivalent to observing θ_N directly. In the more general case where both θ_N and θ_S are unknown, such sharp posteriors are not possible. Still the planners know all the combinations of θ_N and θ_S consistent with μ. Depending on the regional uncertainties σ_N and σ_S, some of these combinations will be more likely than others. The planners can therefore calculate the expected marginal abatement cost in both jurisdictions, conditional on μ and/or post-trade emissions:

$$\begin{aligned}\mathbb{E}[MB \mid \mu] = \mathbb{E}[\theta_N \mid \mu] - b_N e_N &= \mu\frac{\mathbb{E}[\mu\theta_N]}{\mathbb{E}[\mu^2]} - b_N e_N \\ &= \mu\frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S} - b_N e_N \\ &= \frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S} b_S e_S - \frac{\sigma_S^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S} b_N e_N.\end{aligned} \tag{3.25}$$

When $e_i \neq 0$, $i = N, S$, expression (3.25) is troubling: the initial cap $e_N + e_S = E = 0$ is set at the level that is efficient conditional on $\theta_N = \theta_S = 0$, or $MB_N = MB_S = 0$. Upon learning $\mu \neq 0$, however, the planners no longer think that $MB_i = 0$ since their posterior belief $\mathbb{E}[MB \mid \mu]$ is 0 only if $e_N = e_S = 0$, see (3.25). Indeed, having learned μ the planners hold the following posterior beliefs on (θ_N, θ_S):

$$\begin{aligned}\hat{\theta}_N^\mu = \mathbb{E}[\theta_N \mid \mu] &= \frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}\mu = \frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}(b_N e_N - b_S e_S) \\ \hat{\theta}_S^\mu = \mathbb{E}[\theta_S \mid \mu] &= -\frac{\sigma_S^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}\mu = \frac{\sigma_S^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}(b_S e_S - b_N e_N).\end{aligned} \tag{3.26}$$

It is immediate that $\hat{\theta}_i^\mu = 0$ only if $\mu = 0$. To see why this signals an inefficient initial cap, recall that marginal climate damages due to emissions are equal to $c \cdot (e_N + e_S)$, which is 0 when $e_N + e_S = 0$. At the same time, conditional on μ expected marginal benefits from emissions are given by (3.25), and these 0 only if $\mu = 0$, meaning that for all $\mu \neq 0$ the initial cap is inefficient. Indeed, conditional on beliefs $(\hat{\theta}_N^\mu, \hat{\theta}_S^\mu)$ the expected optimal emission levels e_N^O and e_S^O are determined by:

$$c \cdot (e_N^O + e_S^O) = \hat{\theta}_N^\mu - b_N e_N^O = \hat{\theta}_S^\mu - b_S e_S^O, \tag{3.27}$$

which says that marginal damages from pollution must be equal to expected marginal benefits in both jurisdictions conditional on the planners' posterior beliefs $(\hat{\theta}_N^\mu, \hat{\theta}_S^\mu)$.

We seek a policy that implements (3.27) for all μ; that is, we want to solve the asymmetric information problem using aggregate market signals [34, 97]. Moreover, like standard Linking the policy must guarantee that marginal benefits from emissions are equal across jurisdictions whether or not the planners' beliefs $(\hat{\theta}_N^\mu, \hat{\theta}_S^\mu)$ turn out correct:

$$\theta_N - b_N e_N^O = \theta_S - b_S e_S^O \quad \text{for all } \theta_N, \theta_S. \tag{3.28}$$

The policy that implements both (3.27) and (3.28) is called Optimal Linking.

We make two observations. First, if an Optimal Linking policy implements (3.27), then the information on marginal benefits contained in jurisdictions' choices of emissions levels is again summarized by $\mu = b_N e_N^O - b_S e_S^O = \theta_N - \theta_S$. Compared to standard Linking, though, the emission levels are optimal not with respect to the prior belief that $\theta_N = \theta_S = 0$ but with respect to the posterior belief $(\theta_N, \theta_S) = (\hat{\theta}_N^\mu, \hat{\theta}_S^\mu)$. Thus, an Optimal Linking policy adjusts the (global) cap in response to the private information revealed in emission levels.

Second, an Optimal Linking policy allows firms to exchange emissions allowances "ton-for-ton". This requirement is necessary for allocative efficiency: any other trading basis creates incentives for firms to exchange allowances beyond the point where the marginal benefit of emissions is equal across all firms and jurisdictions, contradicting (3.28). Thus, a "trading ratio" on allowances cannot be part of an Optimal Linking policy.

Combining these two observations, one can show that an Optimal Linking policy can be implemented through:

$$e_N^O + e_S^O = E^O = (1 - \delta) e_N^O, \tag{3.29}$$

subject to the constraint that allowances can be traded one for one. Equation (3.29) says that global emissions $e_N^O + e_S^O$ are capped at the level E^O, which itself is endogenous to regional emission levels through $E^O = (1 - \delta) e_N^O$. The parameter δ is endogenous to the structure of our model and given by:

$$\delta = \frac{b_N[\sigma_S^2 - \rho\sigma_N\sigma_S] + c[\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S]}{b_S[\sigma_N^2 - \rho\sigma_N\sigma_S] + c[\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S]}. \tag{3.30}$$

We refer to δ as the *cap-adjustment rate* since it prescribes how the global cap on emissions should be adjusted in response to the demand for emissions in both jurisdictions. Interestingly, the cap-adjustment rate δ may be negative. When this happens, higher emissions in one jurisdiction translate into higher emissions in the other jurisdiction as well. The reason is intuitive: if abatement costs in one jurisdiction are very unpredictable yet strongly correlated to those in the other, high abatement costs in the latter are likely matched by equally high costs in the former.

Practically, Optimal Linking can be thought of as a policy that proceeds in three simple "steps":

1. The planners issue a total number $E = 0$ of allowances;
2. Firms exchange emission on a one-to-one basis both within and across jurisdictions;
3. Conditional on the net number of allowances traded, the planners buy or auction extra allowances until the total number of allowances available for use is E^O.

Proposition 5. *Optimal Linking is the best possible cap and trade policy using only information on quantities. Expected welfare losses under an Optimal Linking policy are given by:*

$$L^O = \frac{1}{2}\frac{b_N + b_S}{cb_N + cb_S + b_N b_S}\frac{(1-\rho)(1+\rho)\sigma_N^2\sigma_S^2}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}. \tag{3.31}$$

Proof. The first part of the proposition is true by construction, i.e. see (3.27) and (3.28). The expression for L^O requires a lengthy derivation and is relegated to the Appendix. □

Note that although an Optimal Linking policy operates via the pre-defined "rule" (3.29), it does not require us to assume that planners commit to this rule [*c.f.* 21]. Once the planners observe μ, their incentive is to adjust the global cap to the level prescribed by our Optimal Linking policy since this is expected to be optimal conditional on their posterior beliefs. Indeed, if the planners had somehow agreed upon another emissions-based updating principle, they would want to deviate to our Optimal Linking rule.[8]

[8]Evidently we do assume that the policymakers commit to updating their policy using information on emissions only; within this class of policy instruments, no further commitment-assumptions are needed.

We emphasize that Optimal Linking policy does not involve a "trading ratio" on allowances [76]. Trading ratios will perform strictly worse than Optimal Linking. To understand why, suppose the planners would impose a trading ratio $\alpha \neq 1$ on allowances such that an allowance worth one ton of emissions in North is worth α tons on emissions in South. Under such a regime, firms would continue to trade allowances across jurisdictions up until the point where $\theta_N - b_N e_N = \alpha(\theta_S - b_S e_S)$, i.e. until the ratio marginal benefits from emissions between North and South is α. This is in direct contradiction with (3.28) and the notion of efficiency, which says that marginal benefits should be exactly equal across jurisdictions. Thus, even if a trading ratio could, in principle, implement the same expected optimal global cap E^O as an Optimal Linking policy, the resulting distribution of abatement efforts will be strictly less efficient.

An optimal linkage performs remarkably well. When uncertainty about abatement costs is strongly asymmetric across jurisdictions ($\sigma_N/\sigma_S \to 0$ or ∞), or when abatement costs are highly correlated ($\rho \to \pm 1$), optimal linking allows for welfare levels very close to the full information Social Optimum. This reflects the planners' great scope for learning in these cases.

Corollary 1. *Where the planners have perfect information about one of the two linked jurisdictions ($\sigma_i = 0$ for $i \in \{N, S\}$), or when abatement costs are perfectly correlated ($\rho = \pm 1$), Optimal Linking implements the first best levels of emissions.*

Even though asymmetric *information* leads to welfare losses, asymmetric *uncertainty* compensates for part (and, in extreme cases, all) of these losses.[9]

Another way to see the great advantage of an optimal linkage is to compare its welfare performance with that of a classic linking policy:

$$\frac{L^O}{L^L} = \frac{(b_N^2 + b_S^2 + 2b_N b_S)(1+\rho)\sigma_N\sigma_S}{b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S \rho\sigma_N\sigma_S} \cdot \frac{(1-\rho)\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}. \tag{3.32}$$

As we expect from Corollary 1, an optimal linkage performs much better than classic linking ($L^O/L^L \to 0$) when uncertainty is highly asymmetric or when abatement costs are strongly correlated ($\rho \to \pm 1$). If we believe that abatement costs are driven by macroeconomic conditions and available technologies they likely are strongly correlated across jurisdictions indeed – this makes a compelling case for optimal (rather than a standard) linking of the cap and trade schemes. Interestingly, though the absolute levels of welfare losses under both classic an optimal linking depend

[9]For a simple illustration of this point, suppose $b_N = b_S = b$ and $\rho = 0$. (i) When uncertainty is perfectly symmetric, i.e. $\sigma_N = \sigma_S = \sigma$, expected welfare losses under an Optimal Linking regime are strictly positive: $L^O = (1/2)(1/(b+2c))\sigma^2 > 0$. (ii) When uncertainty is highly asymmetric, i.e. $\sigma_N/\sigma_S \to 0$ or $\sigma_N/\sigma_S \to \infty$, expected welfare losses under an Optimal Linking regime vanish: $L^O \to 0$.

on climate damages through c, the relative performance of an optimal linkage is independent of the slope of climate damages.

We recall that, though global welfare increases after establishing an optimal linkage, individual jurisdictions may still be worse off. A jurisdiction in which abatement costs are relatively predictable may, through linking, expose itself to the volatile abatement costs in the other jurisdiction and therefore import a variable allowance price [78]. To the extent that such concerns are important for real world linkages, our optimal linking policy offers some relief.

Proposition 6. *Optimally linked cap and trade schemes admit lower price volatility than classically linked cap and trade schemes:*

$$\mathbb{E}\left[\left(p^{OL}\right)^2\right] \leq \mathbb{E}\left[\left(p^{L}\right)^2\right]. \tag{3.33}$$

Though it is still possible that an individual jurisdiction experiences higher allowance price volatility after optimally linking cap and trade schemes, this effect (if it occurs) will be less severe than under standard linking. Note that with inter*temporal* trading of permits, an endogenous cap also reduces price volatility, see [56].

Optimal Linking is the best the planners can do when using only information on quantities to update their beliefs. From a theoretical viewpoint, the limitation to quantity-information is arbitrary. If the planners are willing to use both (post-trade) emissions and allowance prices, they can perfectly back out the marginal abatement cost function in each jurisdiction i (whether linked or not). To see this, we rewrite firms' inverse demand function (3.4) to obtain:

$$\theta_i = p_i + b_i e_i. \tag{3.34}$$

An ideal policy uses information on both prices and quantities to pin down θ_i in each jurisdiction $i = N, S$ and, given these, adjusts the caps so that emission levels end up in the Social Optimum. Our first and foremost recommendation is therefore to implement a policy along those lines.

It is important to note that the ideal instrument is continuous in prices and emissions. A simple price collar – often proposed in the context of cap and trade policies – will perform far worse. To our knowledge, there is no literature on optimal price collars. However, we conjecture that an Optimal Linking policy outperforms (optimal) price-collar-based cap adjustments when uncertainty is highly asymmetric or when abatement costs are strongly correlated (which likely they are since abatement costs are largely driven by technological developments and macroeconomic conditions). In these cases, an optimal linkage implements welfare levels very close to the Social Optimum, see Corollary 1.

3.3.4 Prices vs. Quantities

We saw how jurisdictions can optimally link their cap and trade schemes. As an alternative, each jurisdiction could instead levy a carbon tax. We now revisit the classic question of [140] on instrument choice.

We assume that emissions are taxed at an expected optimal rate – that is, taxes are set to minimize (3.12) subject to the constraint that, in equilibrium, firms will emit until the marginal benefit of emissions equal the tax. Recall that p^* is defined as the expected welfare-maximizing carbon price in each jurisdiction, so the expected optimal tax sets $p_N = p_S = 0$. We may therefore invoke (3.10) and (3.14) to derive expected welfare losses when both jurisdictions tax emissions:

$$L^{tax} = \frac{1}{2}\left(\frac{c}{b_N b_S}\right)^2 \frac{b_N + b_S}{cb_N + cb_S + b_N b_S}(b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S \rho\sigma_N\sigma_S). \tag{3.35}$$

All else equal, the expected welfare loss when jurisdictions tax emissions is increasing in c, the marginal climate damage. We can now compare (3.35) and (3.31), which yields the following proposition.

Proposition 7. *Optimally Linked cap and trade schemes are favored over Taxes if and only if:*

$$\frac{(1+\rho)\sigma_N\sigma_S}{b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S\rho\sigma_N\sigma_S}\frac{(1-\rho)\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S} < \left(\frac{c}{b_N b_S}\right)^2 \tag{3.36}$$

Inequality (3.36) is likely satisfied when both regions have strongly asymmetric uncertainty ($\sigma_N/\sigma_S \to 0$ or ∞) or when abatement costs are highly correlated ($\rho \to \pm 1$). This should not come as a surprise: Corollary 1 showed that precisely in these cases two optimally linked cap and trade schemes implement welfare levels very close to the complete information social optimum. Proposition 7 once again underlining the real-world relevance of optimal linking regime.

3.4 Discussion and Conclusions

3.4.1 Contributions and Limitations

This paper studies the problem of linking cap and trade schemes under uncertainty. We design a novel Optimal Linking policy that can greatly improve the global welfare performance of cap and trade schemes. Although the benefits and costs of linking cap and trade schemes are frequently discussed in the literature [38, 39, 47, 48, 78, 79, 107], ours is the first paper to explore what an optimal linkage might look like.

The core principle of an Optimal Linking policy is to extract private information from firms' emission decisions and, in response, adjust the (global) cap on emissions according to a simple pre-defined rule. Our policy thus uses aggregate market signals to solve the asymmetric information problem [34, 97]. Importantly, Optimal Linking does not use "trading ratios" on allowances [76] – though effectively causing an adjustment of the global cap indeed, a trading ratio incentivizes firms to trade allowances beyond the mere equalization of marginal benefits and this is inefficient in the case of a global pollutant. Moreover, even though our policy operates through a pre-defined and commonly known rule, it does not rely on commitment [*c.f.* 21].

An important limitation of our analysis is the assumption that policymakers use only information on emissions to update the (global) cap. Using both price- and quantity- information, the planners could do far better and implement the first-best level of welfare. Importantly, such a policy would have to be continuous in prices and emissions. A simple price collar [44, 49, 77] will continue to exhibit equilibrium inefficiency. It is not clear whether a price collar performs better than an Optimal Linking policy; we hypothesize that it will not when emission benefits are strongly correlated between the jurisdictions since, in that case, Optimal Linking implements welfare levels very close to the first-best.

Cap and trade schemes are typically dynamic, i.e. they regulate emissions in multiple periods and allow for the use of allowances issued in one (earlier) period to cover emissions emitted in another (later). It is not obvious how two dynamic cap and trade scheme should ideally be linked. For example, how would the aggregate cap respond when firms in one jurisdiction buy allowances from the other and then keep them for future use? In this case, the mere number of allowances traded is not informative about the regional benefit functions (though note that the number of allowances surrendered per jurisdiction still is; that is, the equivalence of allowance trading and emissions in a given period breaks down in a dynamic setting). Similarly, it is not clear how a dynamic cap and trade policy should respond to the composition of allowances surrendered or stored. A complete theory of linking should account for the fact cap and trade schemes can be dynamic.

The Optimal Linking policy is derived under strong assumptions regarding functional forms. While we do not investigate the robustness of our results to more general specifications, we nevertheless believe that our key insights generalize. Whenever firms are allowed to trade allowances, the resulting allocation of emissions must be such that marginal benefits are equal for all firms (if not, firms can continue to make mutually beneficial trades, which we may reasonably assume they will). The fact that an observed distribution of allowances implies marginal benefit equalization allows a policymaker to construct posterior beliefs on the true marginal benefit function in each jurisdiction. When this posterior deviates from the prior belief that was used to set the global cap, the initial cap may turn out inefficient, which motivates policy updating. Similarly, the idea that asymmetric uncertainty can improve the performance of a well-designed cap and trade scheme with an endogenous cap seems fairly robust: belief updating is always easier when there is a strong (relative) "anchor" to update beliefs upon.

We pursue a top-down approach toward linking. Our Optimal Linking policy is derived from global welfare maximization. Unfortunately, while expected global welfare is strictly higher under an Optimal Linking regime compared to local cap and trade, regional welfare may be lower since a relatively stable jurisdiction may, through linking, expose itself to imported uncertainty from another. Since global welfare is strictly higher it is of course possible to construct side payments such that each jurisdiction expects to benefit from an Optimal Linkage; if, however, side payments are (politically) infeasible, individual jurisdictions may opt out of an Optimal Linkage. Our analysis is therefore best seen as an attempt to formulate the kind of linking policy an international agreement like the Paris Agreement or its successors might stimulate.

Finally, we treat uncertainty in a very particular way. Our analysis considers the case in which the intercept of the marginal abatement function is private information of the firms; however, the planners nevertheless know all other parameters of the emissions benefit function. Similarly, we assume that the environmental damage function to be perfectly known. Future work might relax these restrictive assumptions.

3.4.2 Policy Implications

Cap and trade schemes have become a major policy instrument in the fight against climate change. In Europe alone, roughly 45% of greenhouse gas emissions are regulated by EU ETS, the world's largest market for carbon. As more and more cap and trade schemes are erected, linking has become a prominent policy issue – in fact, multilateral linking is explicitly suggested by Article 6 of the Paris agreement and linkages between local schemes already exist. The are linkages between EU ETS and the Swiss ETS, between RGGI and Quebec, between Quebec and California. The up-and-coming carbon markets of China and the post-Brexit UK will create new possibilities for linking. Given the large amount of money and CO_2 involved in cap and trade, and given the increasing prevalence of linkages between jurisdictional schemes, constructive ideas on optimal linking are called for. This paper offers some initial thoughts. We have three key messages for efficient policymaking.

First, allowances should be traded "ton-for-ton" between linked schemes to guarantee an efficient distribution of emissions given the aggregate cap. The reason for this requirement is that a trading ratio on allowances [76] would incentivize firms to distribute emissions between jurisdictions beyond the point at which marginal benefits of emissions are the same. Since climate change is indifferent to the source of emissions, such an allocation of emissions would be inefficient.

Second, the aggregate cap on emissions should be adjusted in response to allowance trading – or the demand for emissions – between the jurisdictions. The idea here is that the choice to buy or sell allowances, given an initial cap, reveals information about the marginal benefits due to emissions of the firms involved in the transaction. This information can be used to update the policymakers' beliefs about an efficient global cap, which may result in cap adjustments.

Third, the demand for emissions in a less predictable jurisdiction should have a relatively stronger effect on global emissions in an efficient cap and trade scheme. This condition follows from the observation that if firms choose to re-allocate allowances in a way unforeseen by the policymakers, so their prior beliefs about the true benefit functions were off, then the likeliest explanation is that benefits were "most off" in the unpredictable jurisdiction. Cap adjustments therefore respond more strongly to demand for emissions in the unpredictable jurisdiction.

Our narrative focuses on linking of cap and trade schemes at the level of a jurisdiction. Another, perhaps more natural interpretation of our model is in terms of covering emissions in different sectors, industries, or even countries with a single cap and trade scheme. Consider the aviation sector. Passenger flights outside the European Economic Area are not covered by the EU ETS. To nevertheless reduce emissions in the aviation industry, "the International Civil Aviation Organization (ICAO) agreed on a Resolution for a global market-based measure to address CO2 emissions from international aviation as of 2021. The agreed Resolution sets out the objective and key design elements of the global scheme, as well as a roadmap for the completion of the work on implementing modalities. The Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA, aims to stabilize CO2 emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020."[10] Though it is still unclear how exactly CORSIA and EU ETS will interact, our analysis suggests that a direct incorporation of CORSIA into the EU ETS may be suboptimal. Similarly, our results suggest that trade of allowances between sectors or clearly identified jurisdictions within an existing cap and trade scheme – countries in the EU ETS, states in RGGI, industries in the South Korea ETS – can be made more efficient by incorporating a policy along the lines of our optimal linking regime.

3.4.3 Concluding Remarks

We propose a simple theory of optimal linking. Our results have the potential to greatly increase welfare compared to current practices. The core of an optimal linkage boils down to a basic observation: trading in allowances between schemes signals valuable information about abatement costs in the jurisdictions. An efficient policy aims to incorporate this information and adjusts the linked global cap in response to

[10]Retrieved from https://ec.europa.eu/clima/policies/transport/aviation_en

allowance trading. We pin down a precise analytic formulation for such endogenous policy updating.

There are various ways to adjust the global cap in response to trade flows, but under an optimal linkage, firms are allowed to exchange allowances one-for-one both within and across schemes. Thus, our optimal linking policy cannot rely on "trading ratios" for emissions allowances [76]. While trading ratios on allowances do indeed endogenize the (global) cap in response to trading [76], they also disturb individuals firms' incentives away from an exact equalization of marginal abatement costs. A straightforward way to achieve this is to either inject new permits or buy back already issued ones as called for by the observed trade flows. This is not too complicated; [73] analyzes a buyback policy in a dynamic model of the EU ETS.

An important concept is asymmetric uncertainty. When two schemes trade allowances, information on *relative* abatement costs is revealed. But when the schemes are asymmetrically uncertain, this information on relative abatement costs can be used to make (sharp) predictions about *absolute* abatement costs as well. The same is not possible when trade between symmetrically uncertain schemes is observed. Our results suggest that the study of asymmetric uncertainty deserves a more prominent place in environmental economics.

Our theory is preliminary and does not address several aspects of real life emission trading. Most large-scale cap and trade schemes are dynamic and allow covered industries to bank (and sometimes borrow) allowances across periods. How two dynamic cap and trade schemes should optimally be linked will likely depend on details of the dynamic policy. Similarly, it remains unclear how two cap and trade schemes, each with their own price collar on allowances, should best be linked. We leave an exploration of these and other aspects for future research.

3.A Derivations and Proofs

DERIVATION OF (3.20):

Combining the definition with the firms' FOCs, (3.4), we find the change in permit use by jurisdiction:

$$\Delta^L e_N = \frac{\theta_N - \theta_S}{b_N + b_S} \tag{3.37}$$

$$\Delta^L e_S = \frac{\theta_S - \theta_N}{b_N + b_S}. \tag{3.38}$$

PROOF OF PROPOSITION 4:

Proof. We only need to compare welfare losses under a linked cap and trade regime, equation (3.20), to those under jurisdictional cap and trade, equation (3.16). Linking outperforms regional cap and trade iff:

$$\frac{b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S \rho\sigma_N\sigma_S}{b_N + b_S} < (c+b_S)\sigma_N^2 + (c+b_N)\sigma_S^2 - 2c\rho\sigma_N\sigma_S$$

$$\Longleftrightarrow$$

$$\frac{2\rho\sigma_N\sigma_S}{\sigma_N^2+\sigma_S^2} < \frac{cb_N + cb_S + b_N b_S}{cb_N + cb_S},$$

which is always true as the LHS is below and the RHS is above one. □

DERIVATION OF (3.30):

Regional and global deviations from Socially Optimal permit use are given by:

$$\Delta^O e_N = \frac{b_S}{b_N+\delta b_S}\frac{[\delta b_S - c(1-\delta)]\theta_N + [b_N + c(1-\delta)]\theta_S}{cb_N + cb_S + b_N b_S} \tag{3.39}$$

$$\Delta^O e_S = \frac{b_N}{b_N+\delta b_S}\frac{[\delta b_S - c(1-\delta)]\theta_N + [b_N + c(1-\delta)]\theta_S}{cb_N + cb_S + b_N b_S} \tag{3.40}$$

$$\Delta^O Q = \frac{b_N + b_S}{b_N+\delta b_S}\frac{[\delta b_S - c(1-\delta)]\theta_N + [b_N + c(1-\delta)]\theta_S}{cb_N + cb_S + b_N b_S}. \tag{3.41}$$

Define

$$\xi := \frac{b_N + c(1-\delta)}{b_N + \delta b_S} \implies 1-\xi := \frac{\delta b_S - c(1-\delta)}{b_N+\delta b_S}. \tag{3.42}$$

Welfare losses can now be written as:

$$\begin{aligned} L^O &= \frac{1}{2}\frac{c(b_N+b_S)^2 + b_N^2 b_S + b_N b_S^2}{(cb_N + cb_S + b_N b_S)^2}\mathbb{E}\left[(1-\xi)\theta_N + \xi\theta_S\right]^2 \\ &= \frac{b_N+b_S}{2}\frac{(1-\xi)^2\sigma_N^2 + \xi^2\sigma_S^2 + 2\xi(1-\xi)\rho\sigma_N\sigma_S}{cb_N + cb_S + b_N b_S}. \end{aligned} \tag{3.43}$$

If for notational convenience, we define:

$$\psi := \frac{1}{2}\frac{b_N + b_S}{cb_N + cb_S + b_N b_S}, \tag{3.44}$$

it is straightforward to derive:

$$\frac{\partial}{\partial \xi}\frac{L^O}{\psi} = 2\xi\sigma_S^2 - 2(1-\xi)\sigma_N^2 + 2(1-\xi)\rho\sigma_N\sigma_S - 2\xi\rho\sigma_N\sigma_S. \tag{3.45}$$

The welfare-maximizing ξ^* therefore satisfies:

$$\xi^* = \frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}. \tag{3.46}$$

From the definition of ξ, the optimal cap-adjustment rate δ^* follows:

$$\delta^* = \frac{(b_N + c)[\sigma_S^2 - \rho\sigma_N\sigma_S] + c[\sigma_N^2 - \rho\sigma_N\sigma_S]}{(b_S + c)[\sigma_N^2 - \rho\sigma_N\sigma_S] + c[\sigma_S^2 - \rho\sigma_N\sigma_S]}, \tag{3.47}$$

as given.

PROOF OF PROPOSITION 5:

Proof. Plugging (3.46) in (3.43), we find:

$$\begin{aligned}
\frac{L^O}{\psi} &= \left[\frac{\sigma_S^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}\right]^2 \sigma_N^2 + \left[\frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}\right]^2 \sigma_S^2 \\
&\quad + \left[\frac{\sigma_S^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}\right]\left[\frac{\sigma_N^2 - \rho\sigma_N\sigma_S}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S}\right]\rho\sigma_N\sigma_S \\
&= \frac{(1-\rho^2)\sigma_N^2\sigma_S^2}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S} \\
&\Longrightarrow \\
L^O &= \frac{1}{2}\frac{b_N + b_S}{cb_N + cb_S + b_N b_S}\frac{(1-\rho^2)\sigma_N^2\sigma_S^2}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S},
\end{aligned}$$

as stated. This is strictly lower than the welfare loss under traditional Trading if and only if:

$$\begin{gathered}
L^L - L^O \geq 0 \\
\Longrightarrow \\
\frac{1}{b_N + b_S}\frac{b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S\rho\sigma_N\sigma_S}{cb_N + cb_S + b_N b_S} - \frac{b_N + b_S}{cb_N + cb_S + b_N b_S}\frac{(1-\rho^2)\sigma_N^2\sigma_S^2}{\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S} \geq 0 \\
\Longrightarrow \\
(\sigma_N^2 + \sigma_S^2 - 2\rho\sigma_N\sigma_S)(b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S\rho\sigma_N\sigma_S) - (1-\rho^2)(b_N^2 + b_S^2 + 2b_N b_S)\sigma_N^2\sigma_S^2 \geq 0 \\
\Longrightarrow \\
[(b_S\sigma_N^2 - b_N\sigma_S^2) + (b_N - b_S)\rho\sigma_N\sigma_S]^2 \geq 0,
\end{gathered}$$

which is always true. □

PROOF OF PROPOSITION 6:

Proof. We derived quantity derivations under both policies. Prices are equal in both jurisdictions, so without loss of generality we can solve for price deviations in jurisdiction 1:

$$\begin{aligned}
\Delta^L p_N &= \frac{b_S\theta_N + b_N\theta_S}{b_N + b_S} \\
\Delta^{OL} p_N &= \frac{\delta b_S\theta_N + b_N\theta_S}{b_N + \delta b_S}.
\end{aligned}$$

Thus:

$$\begin{aligned}
\mathbb{E}\left[\left(\Delta^L p\right)^2\right] &= \frac{b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2b_N b_S\rho\sigma_N\sigma_S}{b_N^2 + b_S^2 + 2b_N b_S} \\
\mathbb{E}\left[\left(\Delta^{OL} p\right)^2\right] &= \frac{\delta^2 b_S^2\sigma_N^2 + b_N^2\sigma_S^2 + 2\delta b_N b_S\rho\sigma_N\sigma_S}{b_N^2 + \delta^2 b_S^2 + 2\delta b_N b_S}.
\end{aligned}$$

Writing these out, we obtain:

$$\mathbb{E}\left[\left(\Delta^{OL}p\right)^2\right] < \mathbb{E}\left[\left(\Delta^{L}p\right)^2\right] \iff (\delta - 1)\left[b_S\left(\sigma_N^2 - \rho\sigma_N\sigma_S\right) - b_N\left(\sigma_S^2 - \rho\sigma_N\sigma_S\right)\right] < 0.$$

This condition is always satisfied. $\square$

CHAPTER 4

The Global Climate Game

4.1 Introduction

Climate change is a coordination failure of existential proportions. In order to reduce greenhouse gas emissions and prevent dangerous climate change, large-scale investments in clean technologies are necessary. These investments, however, are costly and their benefits imperfectly understood. Thus one faces a strategic situation in which clean investment are required on behalf of multiple agents, leading to a coordination problem under uncertainty. In this paper, I present what is perhaps the most bare-bones model to study this type of decision problem. Players invest in competing technologies. One technology is cheap and dirty, the other expensive but clean, and investments exhibit technological spillovers.

My first contribution is to show that uncertainty about the clean technology leads to selection of a unique Bayesian Nash equilibrium. This result is derived using the machinery of global games [31, 51] and resolves complications caused by equilibrium multiplicity often encountered in the literature on clean technologies. As many authors have pointed out, technologies often exhibit technological spillovers or other kinds of strategic complementarities – and these may turn the game into a coordination game with multiple equilibria [2, 4, 13, 18, 35, 66, 74, 80]. There are several reasons why technological investments may exhibit strategic complementarities. Among those discussed in the literature on clean technologies are network effects [32, 63, 88, 100, 110]; cost sharing: [35]; R&D in breakthrough technologies [13, 74]; climate tipping points [17]; climate clubs [119]; technological and knowledge spillovers [2, 3, 4, 46, 67, 96]; social norms [6, 9, 95, 121, 122]; and reciprocity [120].

In much of the environmental literature, equilibrium selection is treated somewhat implicitly and in a way that is not completely satisfactory. Two approaches are especially prevalent. One approach hand-picks, or at minimum focuses on a particular kind of equilibrium. Thus, players may be a priori assumed to pursue symmetric strategies [66, 69], or to coordinate on the Pareto strictly dominant outcome [13, 74].[1]

[1]In this paper, the unique equilibrium will also be in symmetric strategies. Although this is

Another approach treats the coordination problem as theoretically indecisive and relies on lab experiments to make predictions (for experimental studies of coordination games in the context of climate change in particular, see [15, 16, 17, 28, 36]). My explicit focus on equilibrium selection complements these approaches. It provides sharp conditions under which I would expect rational players to coordinate on the Pareto strictly dominant equilibrium of the game.

The unique equilibrium of the game may be inefficient. For intermediately high clean investment benefits, players adopt the dirty technology even though they would be better off were all to adopt the clean technology instead.

My second contribution is the introduction of network subsidies. The issue of taxes and subsidies, or rather policy in general, arises naturally in the present context where investments cause two externalities. One is an environmental externality that derives from the positive environmental effect clean investments have on all players; the other is a network externality deriving from spillovers (strategic complementarities) in clean investments. As I show, using only taxes and subsidies the policymaker can costlessly correct both of these externalities by turning the (expected) efficient action into a strictly dominant action for all players (both in the game of complete information and in the global game). Moreover, I also show that even when taxes (for political or other reasons) are not possible or desirable, the policymaker can correct the network externality at zero cost. The novelty in this is what I call a network subsidy. Like standard subsidies, a network subsidy offers adopters of the clean technology a (financial) reward. In contrast to a standard subsidy scheme, however, the amount of the subsidy upon adoption also depends on how many others adopt the clean technology, and is decreasing in that number. Since adoption of the clean technology is more attractive when the number of other players adopting it is higher due to the technological spillover, it is somewhat intuitive that the network subsidy can decrease in aggregate clean technology adoption without negatively affecting players' incentives. A network subsidy exploits this intuition.

Intuitively, the network subsidy insures adopters of the clean technology against the event they would enjoy few technological spillovers because many others adopted the dirty technology – it offers "protection against defection". In so doing, a network subsidy boosts clean investments and therefore is never claimed. This result is independent of the application to clean technologies and suggests that network subsidies may be worth studying in other contexts where strategic complementarities naturally arise.

The derivation of network subsidies can be considered a restrictive yet simple exercise

somewhat intuitive as my setting is one of symmetric players, I nonetheless allow players to pursue any strategy, including non-symmetric ones. Thus, the fact that the unique equilibrium in my game is in symmetric strategies is a result rather than an assumption.

in mechanism design or implementation theory in which the policumaker aims to make coordination on the efficient outcome of the game a strictly dominant strategy for all players [94, 98, 116]. While mechanism design has been applied to environmental economics and, in particular, emissions mitigation before [8, 40, 103], these papers tend to construct mechanisms that solve the free-rider problem. In this paper, I instead derive a mechanism to overcome the coordination problem. My approach is in this sense complementary to these earlier constributions.

Network subsidies can also be related to the literature on directed technical change and the environment [2, 3, 4, 62]. This literature studies the effect of policy on technology adoption when multiple and (partially) substituable technologies co-exist with differental consequences for social welfare, the environment, and growth. Technologies are often characterized as either clean or dirty and assumed to exhibit technology-specific positive spillovers, with the dirty technology starting off as more advanced. The question asked is then how different kinds of policies – e.g. a carbon tax or R&D subsidies – can be used most efficiently to stimulate large-scale adoption of the clean technology. Importantly, my simple model is much less rich than the types of economies studied in the literature on directed technical change – to mention some important differences, I study a one-period decision problem rather than a repeated game, and in implicitly assuming that technologies are perfectly substitutable I shy away from discussions on the effect of imperfect substitutability on policy. Thus, while a network subsidy might offer a new kind of policy to consider in discussions on directed technical change, more work is required to design network subsidy schemes for the kinds of contexts normally studied in this literature.

In my model, equilibrium selection is catalyzed by uncertainty about the clean technology.[2] The assumption seems realistic. There are many uncertainties surrounding climate change and individual beliefs vary vastly [81]. Within the model, one is free to interpret this uncertainty in different ways. Uncertainty could pertain to the true severity of climate change, the location of a dangerous tipping point, or the true potential of a breakthrough technology. Although many authors have studied the role of incomplete information in the climate context [15, 92, 103], none consider the type of uncertainty with idiosyncratic, player-specific (posterior) beliefs studied here.

The remainder of the paper is structured as follows. In Section 4.2, I present the main model and briefly discuss the game of complete information. In Section 4.3, I add uncertainty to the analysis and show that the global game has a unique equilibrium. Section 4.4 introduces network subsidies, and Section 4.5 concludes.

[2]This type of "global uncertainty" turns the game into a global game. However, other approaches toward equilibrium selection also exist. For example, Poisson games [102, 105, 114, 115], i.e. games in which players are uncertain about the number of other players playing the game. Poisson coordination games have a unique equilibrium as the uncertainty vanishes. Another well-known approach derives equilibrium selection as a dynamic outcome of a process of evolutionary selection [84].

4.2 Main Model

Consider a world consisting of N players. Each player chooses to invest in either of two technologies. The first, called the dirty technology, is cheap and polluting. If a player does not invest in the dirty technology, s/he invests in an expensive but environmentally-friendly clean technology. A natural interpretation of the players would be firms or households.

Compared to investment in the dirty technology, the environmental benefit of investing in the clean technology is $b > 0$. An action for player i is a binary variable $x_i \in \{0,1\}$ such that $x_i = 1$ corresponds to investment in the clean technology while $x_i = 0$ stands for investment in the dirty technology. Let $x = (x_1, x_2, ..., x_N)$ denote the vector of actions played by all players, and let $x_{-i} = (x_j)_{j \neq i}$ be the vector of actions by all players but i. Let $\mathbf{1} = (1, 1, ..., 1)$ be the action vector of all ones, and $\mathbf{0} = (0, 0, ..., 0)$ the action vector of all zeroes. The cost of investing in the dirty technology (play 0) is constant at d. The costs of investing in the clean technology (play 1) depend on the total number of players, n, that invest in clean and are decreasing in n: $c(1) > c(2) > ... > c(N)$. That is, the game exhibits strategic complementarities [25]. I assume that $c(N) > d$.[3]

Combining these elements, the payoff to player i is:

$$\pi_i(x \mid b) = \begin{cases} b \cdot n(x) - d & \text{if} \quad x_i = 0 \\ b \cdot (n(x)) - c(n(x)) & \text{if} \quad x_i = 1 \end{cases}, \tag{4.1}$$

where $n(x)$ is defined as the total number of players playing 1 in x; hence, $n(x) = \sum_{i=1}^{N} x_i$. I define $n(x_{-i})$ as the total number of players other than i that play 1 in x: $n(x_{-i}) = \sum_{j \neq i} x_j$. The set of players $\{1, 2, ..., N\}$, the set of action vectors $x \in \{0,1\}^N$, and the set of payoff functions $\{\pi_i\}$ jointly define a complete information game $G(b)$.[4] I write $G(b)$ for the game of complete information (i.e. with common knowledge of b) to differentiate this game from the global game studied in Section 4.3 where players do not observe b. The choice of b is as key parameter is made for convenience; one could have chosen other parameters instead.

Similar to [99], there are two externalities associated with investment in the clean technology . The first is an *environmental externality* and relates to the parameter b, the positive impact an individual player's investment in the clean technology has on the

[3] This assumption is of no technical importance for the analysis; it buys me the convenience of not having to discuss separately the cases where $d < c(N)$ and $d > c(N)$ in the welfare analysis.

[4] The payoff function (4.1) is extremely simple and one may wonder whether the results derived in this paper are due to its particular specification. Under some additional assumptions, an implication of [51] is that the results on equilibrium selection in the global game (Section 4.3) hold true more generally, see also the discussion following Proposition 10. I did not examine the generalizability of my results on network subsidies (Section 4.4).

environment (and hence payoff) for all other players – think of reduced CO2 emissions. The second is a *network externality* and relates to the investment cost function c, i.e. it captures the fact that a player's investment in the clean technology lowers the cost of clean technological investment for all other players – think of technological or knowledge spillovers. My model is different from [99] in two important dimensions; they study a dynamic model whereas I consider a static game, and theirs is not a global game (Section 3).

The gain from investing in the clean rather than the dirty technology to player i (given b and x_{-i}) is the difference in payoffs between playing $x_i = 1$ and $x_i = 0$. For given x_{-i}, I define

$$\begin{aligned} \Delta_i(x_{-i} \mid b) &= \pi_i(1, x_{-i} \mid b) - \pi_i(0, x_{-i} \mid b) \\ &= b + d - c(n(x_{-i}) + 1). \end{aligned} \tag{4.2}$$

Moreover, if $k = n(x_{-i})$ I write $\Delta_i(k \mid b) = \Delta_i(x_{-i} \mid b)$.

The action $x_i = 1$ is strictly dominant for all $b > c(1) - d$ as for those bs it holds that $\Delta_i(x_{-i} \mid b) > 0$ for all x_{-i}. Alternatively, $x_i = 0$ is strictly dominant for all $b < c(N) - d$. In between, the game has multiple equilibria.

Proposition 8.

(i) $x = \mathbf{1}$ *is a Nash equilibrium of the game for all* $b \geq c(N) - d$*. It is the unique Nash equilibrium for all* $b > c(1) - d$*.*

(ii) $x = \mathbf{0}$ *is a Nash equilibrium of the game for all* $b \leq c(1) - d$*. It is the unique Nash equilibrium for all* $b < c(N) - d$*.*

(iii) $x = \mathbf{1}$ *is Pareto strictly dominant for all* $b > \frac{c(N)-d}{N}$*.*

Proof. This follows from the above dominance argument, together with direct payoff comparisons. □

To smoothen notation, I shall henceforth write $\bar{b} = \frac{c(N)-d}{N}$.

Environmental economists have long recognized the possibility of equilibrium multiplicity in games of technological investments [13, 15, 17, 74, 110]. It motivates the question of equilibrium selection, to which Section 4.3 is devoted. First, however, I offer some final remarks on the complete information game $G(b)$.

[51] have observed that a game such as given by (4.1) is a *potential game* [111]. A game in which each player has two actions is a potential game if there exists a potential function $P : \{0, 1\}^N \to \mathbb{R}$ on action profiles such that the change in any individual player's payoff when switching from one action to the other is always equal to the change in the potential function; that is, for which there exists a function P such that

$P(x_i, x_{-i} \mid b) - P(1 - x_i, x_{-i} \mid b) = \pi_i(x_i, x_{-i} \mid b) - \pi_i(1 - x_i, x_{-i} \mid b)$ for all i. The game $G(b)$ has a potential function $P(x \mid b)$ given by:

$$P(x \mid b) = \begin{cases} \sum_{k=0}^{n(x)-1} \Delta_i(k \mid b) & \text{if } n(x) > 0, \\ 0 & \text{if } n(x) = 0. \end{cases} \tag{4.3}$$

Observe that, for any i and any $x_{-i} \in \{0,1\}^{N-1}$, it holds that $P(1, x_{-i} \mid b) - P(0, x_{-i} \mid b) = \Delta_i(x_{-i} \mid b) = \pi_i(1, x_{-i} \mid b) - \pi_i(0, x_{-i} \mid b)$, confirming that P is a potential function indeed.[5]

A *potential maximizer* is a vector x that maximizes P. One can verify that $\mathbf{1}$ is the unique potential maximizer of $P(x \mid b)$ for all $b + d > \sum_{n=1}^{N} \frac{c(n)}{N}$ whereas $\mathbf{0}$ is the unique potential maximizer of $P(x \mid b)$ for all $b + d < \sum_{n=1}^{N} \frac{c(n)}{N}$. I return to this observation in the next section.

4.3 The Global Climate Game

Strategic complementarities in clean investments drive equilibrium multiplicity under common knowledge of b, the environmental benefit of clean investment. But the assumption of complete information is strong. There are large numbers of uncertainties surrounding many clean technologies's present or future potential.

Uncertainty and signals. For these reasons, I will now study a global game. In the global game G^{ε} the true parameter b is unobserved. Rather, it is assumed that b is drawn from the uniform distribution on $[\underline{B}, \overline{B}]$ where $\underline{B} < c(N) - d$ and $\overline{B} > c(1) - d$ and that each player i receives a private noisy signal b_i^{ε} of b, given by:[6]

$$b_i^{\varepsilon} = b + \varepsilon_i. \tag{4.4}$$

The term ε_i captures idiosyncratic noise in i's private signal. It is common knowledge that ε_i is an i.i.d. draw from the uniform distribution on $[-\varepsilon, \varepsilon]$. I assume that ε is sufficiently small: $2\varepsilon < \min\{c(N) - d - \underline{B}, \overline{B} - c(1) + d\}$. Let $b^{\varepsilon} = (b_i^{\varepsilon})$ denote the vector of signals received by all players, and let b_{-i}^{ε} denote the vector of signals received by all players but j, i.e. $b_{-i}^{\varepsilon} = (b_j^{\varepsilon})_{j \neq i}$. Note that player i observes b_i^{ε} but neither b nor b_{-i}^{ε}. Thus I write $\Phi^{\varepsilon}(\cdot \mid b_i^{\varepsilon})$ for the joint probability function of $(b, b_j^{\varepsilon})_{j \neq i}$ conditional on b_i^{ε}. The timing of the global game G^{ε} is as follows:

1. Nature draws a true b;

---

[5] If $n(x) > 1$, the confirmation is as in the text. If, however, $n(x) = 1$, then one has $P(1, x_{-i} \mid b) - P(0, x_{-i} \mid b) = \sum_{k=0}^{0} \Delta_i(k \mid b) - 0 = \Delta_i(x_{-i} \mid b) = \pi_i(1, x_{-i} \mid b) - \pi_i(0, x_{-i} \mid b)$

[6] In game theory, it is assumed that the game (in this case G^{ε}) is common knowledge; hence, the structure of the uncertainty (the joint distrubution of b and all the signals b_j^{ε}), the possible actions and all the payoff functions are commonly known. For a formal treatment of common knowledge, see [12].

2. Each player i receives its private signal b_i^ε of b;
3. All players simultaneously choose their actions;
4. Payoffs are realized according to the true b and the actions chosen by all players.

In what follows I will take $\varepsilon > 0$ as given and introduce the concepts used to analyze the global game G^ε.

Strategies and strict dominance. Player i receives a signal b_i^ε prior to choosing an action. A strategy p_i for player i in G^ε is a function that assigns to any $b_i^\varepsilon \in [\underline{B} - \varepsilon, \overline{B} + \varepsilon]$ a probability $p_i(b_i^\varepsilon) \geq 0$ with which the player chooses action $x_i = 1$ when s/he observes b_i^ε. I write $p = (p_1, p_2, ..., p_N)$ for a strategy vector. Similarly, I write $p_{-i} = (p_j)_{j \neq i}$ for the vector of strategies for all players but i. Conditional on the strategy vector p_{-i} and a private signal b_i^ε, the expected gain (of choosing $x_i = 1$ rather than $x_i = 0$) to player i is given by:

$$\Delta_i^\varepsilon(p_{-i} \mid b_i^\varepsilon) = \int \Delta_i(p_{-i}(b_{-i}^\varepsilon) \mid b) \, d\Phi^\varepsilon(b, b_{-i}^\varepsilon \mid b_i^\varepsilon). \tag{4.5}$$

I say that the action $x_i = 1$ is strictly dominant at b_i^ε if $\Delta_i^\varepsilon(p_{-i} \mid b_i^\varepsilon) > 0$ for all p_{-i}. Similarly, the action $x_i = 0$ is strictly dominant (in the global game G^ε) at b_i^ε if $\Delta_i^\varepsilon(p_{-i} \mid b_i^\varepsilon) < 0$ for all p_{-i}. When $x_i = 1$ is strictly dominant, I say that $x_i = 0$ is strictly dominated; similarly, when $x_i = 1$ is strictly dominant, I say that $x_i = 1$ is strictly dominated.

Lemma 1. *Consider the global game G^ε. (i) For each player i, the action $x_i = 1$ is strictly dominant at all $b_i^\varepsilon \geq \overline{B}$. (ii) For each player i, the action $x_i = 0$ is strictly dominant at $b_i^\varepsilon \leq \underline{B}$.*

Proof. Observe that $\Delta_i(x \mid b) > 0$ for any x given $b \in [\overline{B} - \varepsilon, \overline{B} + \varepsilon]$. Thus, for $b_i^\varepsilon = \overline{B}$ the integration in (4.5) is over positive terms only and $\Delta_i^\varepsilon(p_{-i} \mid \overline{B}) > 0$ for all p_{-i}. This proves part (i) of the Lemma. The proof of part (ii) relies on a symmetric argument and is therefore omitted. □

Conditional dominance. Let L and R be real numbers. The action $x_i = 1$ is said to be dominant at b_i^ε conditional on R if $\Delta_i^\varepsilon(p_{-i} \mid b_i^\varepsilon) > 0$ for all p_{-i} with $p_j(b_j^\varepsilon) = 1$ for all $b_j^\varepsilon > R$, all $j \neq i$. Similarly, the action $x_i = 0$ is dominant at b_i^ε conditional on L if $\Delta_i^\varepsilon(p_{-i} \mid b_i^\varepsilon) < 0$ for all p_{-i} with $p_j(b_j^\varepsilon) = 1$ for all $b_j^\varepsilon > L$, all $j \neq i$.

The concept of conditional dominance is useful for the following reason. Lemma 1 implies that, for each player j, a strategy p_j of G^ε that prescribes to play $x_j \neq 1$ on a set $b_j^\varepsilon > \overline{B}$ with positive measure is strictly dominated; hence, each player i can effectively assume that each player j will play $p_j(b_j^\varepsilon) = 1$ for all $b_j^\varepsilon \geq \overline{B}$. Eliminating dominated strategies makes, for each player i, $x_i = 1$ strictly dominant for a larger set of observations and hence makes more stratregies of each i strictly dominated; hence, this process can be repeated. Those strategies that survive this process (including elimination of strategies that prescribe playing 1 when that is strictly dominated) are said to survive *iterated elimination of strictly dominated strategies.* For a textbook treatment of iterated dominance, see [123].

Increasing strategies. For some $X \in \mathbb{R}$, let p_i^X denote the particular strategy such that $p_i^X(b_i^\varepsilon) = 0$ for all $b_i^\varepsilon < X$ and $p_i^X(b_i^\varepsilon) = 1$ for all $b_i^\varepsilon \geq X$. I will call p_i^X the *increasing strategy with switching point* X. By $p^X = (p_1^X, p_2^X, ..., p_N^X)$ I denote the strategy vector of increasing strategies with switching point X, and $p_{-i}^X = (p_j^X)_{j \neq i}$. Note that $x_i = 1$ is strictly dominant at b_i^ε conditional on R if and only if $\Delta_i^\varepsilon(p_{-i}^R \mid b_i^\varepsilon) > 0$. Similarly, if $x_i = 0$ is strictly dominant at b_i^ε conditional on L then it must hold that $\Delta_i^\varepsilon(p_{-i}^L \mid b_i^\varepsilon) < 0$.

We now have all notation in place to proceed with the core of the analysis.

Iteration from the right. Let i be arbitrary. Take $p_{-i} = p_{-i}^{\overline{B}}$ and note that $\Delta_i^\varepsilon(p_{-i}^{\overline{B}} \mid b_i^\varepsilon)$ is continuous and monotone non-decreasing in b_i^ε. Moreover, recall from Lemma 1 that $x_i = 1$ is strictly dominant at $b_i = \overline{B}$, so $\Delta_i^\varepsilon(p_{-i}^{\overline{B}} \mid \overline{B}) > 0$. By the same Lemma, I also know that $\Delta_i^\varepsilon(p_{-i}^{\overline{B}} \mid \underline{B}) < 0$. Monotonicity and continuity of $\Delta_i^\varepsilon(p_{-i}^{\overline{B}} \mid b_i^\varepsilon)$ in b_i then imply there exists a point R^1 such that $\underline{B} < R^1 < \overline{B}$ which solves:

$$\Delta_i^\varepsilon(p_{-i}^{\overline{B}} \mid R^1) = 0. \tag{4.6}$$

To any player i, the action $x_i = 1$ is strictly dominant at all $b_i^\varepsilon > R^1$ conditional on $\overline{B}$.

This argument can be repeated and I obtain a sequence $\overline{B} = R^0, R^1, R^2, ...$ For any $k \geq 0$ and R^k such that $\Delta_i^\varepsilon(p_{-i}^{R^k} \mid R^k) > 0$, there exists a $R^{k+1} < R^K$ such that $\Delta_i^\varepsilon(p_{-i}^{R^k} \mid R^{k+1}) = 0$. Induction on k allows for the conclusion that (R^k) is a monotone sequence. Moreover, I also know that $R^k \geq \underline{B}$ for all $k \geq 0$ since $x_i = 0$ is strictly dominant at $b_i^\varepsilon < \underline{B}$. Any bounded monotone sequence must converge. I let R^* denote the limit of sequence (R^k). By the definition of a limit, R^* must satisfy:

$$\Delta_i^\varepsilon(p_{-i}^{R^*} \mid R^*) = 0. \tag{4.7}$$

It follows that a strategy p_i survives iterated elimination of strictly dominated strategies only if $p_i(b_i^\varepsilon) = 1$ for all $b_i^\varepsilon > R^*$, all i.

Iteration from the left. Iterative elimination of strictly dominated strategies yields the point R^* when starting from the right, that is, a range of signals b_i^ε for which $x_i = 1$ is conditionally and strictly dominant. A similar procedure can be executed starting instead from the left, from signals b_i^ε for which $x_i = 0$ is unconditionally and strictly dominant. Since this analysis is symmetric to the procedure discussed above, I will only provide the key steps of the analysis.

From Lemma 1 it is known that $x_i = 0$ is strictly dominant at $b_i^\varepsilon < \underline{B}$. That is, $\Delta_i^\varepsilon(p_{-i}^{\underline{B}} \mid \underline{B}) < 0$. Since it is common knowledge that no player plays a strictly dominated strategy, a payoff maximizing player i then finds a point L^1 such that $x_i = 0$ is strictly dominant $b_i^\varepsilon < L^1$ conditional on $\underline{B}$:

$$\Delta_i^\varepsilon(p_{-i}^{\underline{B}} \mid L^1) = 0. \tag{4.8}$$

Any expected payoff maximizing player i plays $x_i = 0$ for all $b_i^\varepsilon < L^1$. Since this is common knowledge also, I can repeat the argument over and over. What I obtain is a sequence of points (L^k), $k \geq 0$, each term of which is implicitly defined by:

$$\Delta_i^\varepsilon(p_{-i}^{L^k} \mid L^{k+1}) = 0. \tag{4.9}$$

The sequence (L^k) is monotone increasing. It is also bound from above by $\overline{B}$ (or, taking account of (4.7), by R^*). It must therefore converge, and I call its limit L^*. By construction this limit solves:

$$\Delta_i^\varepsilon(p_{-i}^{L^*} \mid L^*) = 0. \tag{4.10}$$

It follows that a strategy p_i survives iterated elimination of strictly dominated strategies only if $p_i(b_i^\varepsilon) = 0$ for all $b_i^\varepsilon < L^*$, all i.

Lemma 2. *(i) If a strategy p_i survives iterated elimination of strictly dominated strategies, then it must hold that $p_i(b_i^\varepsilon) = 1$ for all $b_i^\varepsilon > R^*$. (ii) If a strategy p_i survives iterated elimination of strictly dominated strategies, then it must hold that $p_i(b_i^\varepsilon) = 0$ for all $b_i^\varepsilon < L^*$.*

Proof. Follows immediately from the argument leading up to the Lemma. □

I have derived two limits L^* and R^* that demarcate iterative dominance regions of the signal space. I am going to show that $L^* = R^*$. To prove this, the following result is key.

Proposition 9. *For all X such that $\underline{B} + \varepsilon \leq X \leq \overline{B} - \varepsilon$, the following holds:*

$$\Delta_i^\varepsilon(p_{-i}^X \mid X) = X - \sum_{m=0}^{N-1} \frac{c(m+1)}{N} + d. \tag{4.11}$$

It follows that $\Delta_i^\varepsilon(p_{-i}^X \mid X)$ is strictly increasing in X for all X such that $\underline{B} + \varepsilon \leq X \leq \overline{B} - \varepsilon$.

Proof. First fix $b \in [\underline{B} + \varepsilon, \overline{B} - \varepsilon]$. Each player $j \neq i$ is assumed to play p_j^X, so the probability that $x_j = 1$ is given by

$$\Pr[b_j^\varepsilon > X \mid b] = \Pr[\varepsilon_j > X - b] = \frac{\varepsilon - X + b}{2\varepsilon}, \tag{4.12}$$

for all $X \in [b-\varepsilon, b+\varepsilon]$ while $\Pr[b_j^\varepsilon > X \mid b]$ is either 0 or 1 otherwise. Clearly, $x_j = 0$ is played with the complementary probability (given b and X). Since each ε_j is (conditional on b) drawn independently , the probability that m given players $j \neq i$ play $x_j = 1$ while the remaining $N-m-1$ players play $x_j = 0$ (given p_{-i}^X and b) is therefore:

$$\left[\frac{\varepsilon - X + b}{2\varepsilon}\right]^m \left[\frac{\varepsilon + X - b}{2\varepsilon}\right]^{N-m-1}. \tag{4.13}$$

As there are $\binom{N-1}{m}$ unique ways in which m out of $N-1$ players j can choose $x_j = 1$, the total probability of this happening, as a function of b, is:

$$\binom{N-1}{m}\left[\frac{\varepsilon - X + b}{2\varepsilon}\right]^m \left[\frac{\varepsilon + X - b}{2\varepsilon}\right]^{N-m-1}. \tag{4.14}$$

When m players $j \neq i$ play $x_j = 1$, the cost of playing $x_i = 1$ to player i is $c(m+1)$.

The derivation so far took b as a known quantity. I now take account of the fact that player i does not observe b directly but only a noisy signal b_i^ε. Given $p_{-i} = p_{-i}^X$ and $b_i^\varepsilon = X$, the expected gain to player i from playing $x_i = 1$ rather than $x_i = 0$ becomes:

$$\begin{aligned}\Delta_i^\varepsilon(p_{-i}^X \mid X) =& \frac{1}{2\varepsilon}\int_{X-\varepsilon}^{X+\varepsilon} b\,db + d\\ &- \sum_{m=0}^{N-1} c(m+1)\binom{N-1}{m}\frac{1}{2\varepsilon}\int_{X-\varepsilon}^{X+\varepsilon}\left[\frac{\varepsilon - X + b}{2\varepsilon}\right]^m \left[\frac{\varepsilon + X - b}{2\varepsilon}\right]^{N-m-1} db \end{aligned} \tag{4.15}$$

$$=X + d - \sum_{m=0}^{N-1} c(m+1)\binom{N-1}{m}\int_0^1 q^n(1-q)^{N-m-1}dq \tag{4.16}$$

$$=X + d - \sum_{m=0}^{N-1} c(m+1)\frac{(N-1)!}{m!\,(N-m-1)!}\frac{m!\,(N-m-1)!}{N!} \tag{4.17}$$

$$=X + d - \sum_{m=0}^{N-1}\frac{c(m+1)}{N}, \tag{4.18}$$

as given. Equation (4.15) takes the expression for $\Delta_i(m \mid b)$ given in (4.2) and integrates over b and m, given $b_i^\varepsilon = X$ and $p_{-i} = p_{-i}^X$. Equation (4.16) relies on integration by substitution (using $q = 1/2 - (X-b)/2\varepsilon$) to rewrite the last integral in (4.15). Equation (4.17) rewrites both the integral in (4.16) and the the binomial coefficient $\binom{N-1}{m}$ in terms of factorials. Equation (4.18) simplifies. □

From the definitions of R^* and L^* given by (4.7) and (4.10), using Proposition 9, one can conclude that $L^* = R^*$. I henceforth write B^* where $B^* = L^* = R^*$. The point

B^* is given by:

$$B^* = L^* = R^* = \sum_{n=1}^{N} \frac{c(n)}{N} - d. \tag{4.19}$$

Thus, if a strategy p_i survives iterated elimination of strictly dominated strategies, then it must hold that $p_i(b_i^\varepsilon) = p_i^{B^*}(b_i^\varepsilon)$ for all $b_i^\varepsilon \neq B^*$. The action prescribed by a strategy p_i that survives iterated dominance can differ from that prescribed by $p_i^{B^*}$ only in the measure-zero event that $b_i^\varepsilon = B^*$. I refer to this by saying that G^ε has an *essentially unique* strategy vector surviving iterated elimination of strictly dominated strategies.

Proposition 10. *For all ε such that $2\varepsilon < \min\{c(N)-d-\underline{B}, \overline{B}-c(1)+d\}$, the strategy vector p^{B^*} is the essentially unique strategy vector surviving iterated elimination of strictly dominated strategies of the game G^ε. In particular, if, for any player i, the strategy p_i survives iterated elimination of strictly dominated strategies, then p_i must satisfy $p_i(b_i^\varepsilon) = p_i^{B^*}(b_i^\varepsilon)$ for all $b_i^\varepsilon \neq B^*$.*

I derive Proposition 10 for general $\varepsilon > 0$ provided the assumption that b and ε_i (all i) are drawn independently from the uniform distribution (which is symmetric for ε_i). For the limit as $\varepsilon \to 0$, [51] establish the very general result that *any* global game with strategic complementarities in which b is drawn from any continuous density with connected support and each ε_i is drawn independently from any (possible player-specific) atomless density has an essentially unique strategy vector surviving iterated elimination of strictly dominated strategies in the limit as $\varepsilon \to 0$. Moreover, for potential games the equilibrium selected is noise independent, meaning that (in the limit) the strategy vector found in Proposition 10 generalizes to far more general distributions than assumed here.[7]

Recall that a strategy vector $p = (p_1, p_2, ..., p_N)$ is a Bayesian Nash equilibrium (BNE) of G^ε if for any p_i and any b_i^ε it holds that:

$$p_i(b_i^\varepsilon) \in \arg\max_{x_i \in \{0,1\}} \pi_i^\varepsilon(x_i, p_{-i}(b_{-i}^\varepsilon) \mid b_i^\varepsilon), \tag{4.20}$$

where $\pi_i^\varepsilon(x_i, p_{-i}(b_{-i}^\varepsilon) \mid b_i^\varepsilon) = \int \pi_i(x_i, p_{-i}(b_{-i}^\varepsilon) \mid b)\, d\Phi^\varepsilon(b, b_{-i}^\varepsilon \mid b_i^\varepsilon)$. It is therefore immediate that p^{B^*} is a BNE of G^ε. The following proposition establishes a much stronger result: if the strategy vector $p = (p_i)$ is a BNE of G^ε, then for each p_i it must hold that $p_i(b_i^\varepsilon) = p^{B^*}(b_i^\varepsilon)$ for all $b_i^\varepsilon \neq B^*$. I say that G^ε has an essentially unique BNE.

Proposition 11. *The strategy vector p^{B^*} is the essentially unique Bayesian Nash equilibrium of the game G^ε. In particular, any equilibrium strategy p_i satisfies $p_i(b_i^\varepsilon) = p_i^{B^*}(b_i^\varepsilon)$ for all $b_i^\varepsilon \neq B^*$ and all players i.*

[7] In particular, the reader is referred to their result on (local) potential games with own-action quasi-concave payoffs, i.e. Theorem 4.

Proof. Let p be a BNE of G^ε. For any player i, define

$$\underline{b}_i = \inf\{b_i^\varepsilon \mid p_i(b_i^\varepsilon) > 0\}, \tag{4.21}$$

and

$$\overline{b}_i = \sup\{b_i^\varepsilon \mid p_i(b_i^\varepsilon) < 1\}. \tag{4.22}$$

Observe that $\underline{b}_i \leq \overline{b}_i$. Now define

$$\underline{b} = \min\{\underline{b}_i\}, \tag{4.23}$$

and

$$\overline{b} = \max\{\overline{b}_i\}. \tag{4.24}$$

By construction, $\overline{b} \geq \overline{b}_i \geq \underline{b}_i \geq \underline{b}$. Observe that p is a BNE of G^ε only if, for each i, it holds that $\Delta_i^\varepsilon(p_{-i}(b_{-i}^\varepsilon) \mid \underline{b}_i) \geq 0$. Consider then the expected gain $\Delta_i^\varepsilon(p_{-i}^{\underline{b}}(b_{-i}^\varepsilon) \mid \underline{b}_i)$. It follows from the definition of $\underline{b}$ that $p^{\underline{b}}(b^\varepsilon) \geq p(b^\varepsilon)$ for all b^ε. The implication is that, for each i, $\Delta_i^\varepsilon(p_{-i}^{\underline{b}}(b_{-i}^\varepsilon) \mid \underline{b}_i) \geq \Delta_i^\varepsilon(p_{-i}(b_{-i}^\varepsilon) \mid \underline{b}_i) \geq 0$. From Proposition 9 then follows that $\underline{b} \geq B^*$.

Similarly, if p is a BNE of G^ε then, for each i, it must hold that $\Delta_i^\varepsilon(p_{-i}(b_{-i}^\varepsilon) \mid \overline{b}_i) \leq 0$. Consider now the expected gain $\Delta_i^\varepsilon(p_{-i}^{\overline{b}}(b_{-i}^\varepsilon) \mid \overline{b}_i)$. It follows from the definition of $\overline{b}$ that $p^{\overline{b}}(b^\varepsilon) \leq p(b^\varepsilon)$ for all b^ε. For each i it therefore holds that $\Delta_i^\varepsilon(p_{-i}^{\overline{b}}(b_{-i}^\varepsilon) \mid \overline{b}_i) \leq \Delta_i^\varepsilon(p_{-i}(b_{-i}^\varepsilon) \mid \overline{b}_i) \leq 0$. Hence $\overline{b} \leq B^*$.

Since $\underline{b} \leq \overline{b}$ while also $\underline{b} \geq B^*$ and $\overline{b} \leq B^*$ it must hold that $\underline{b} = \overline{b} = B^*$. Moreover, since $p^{\underline{b}} \geq p$ while also $p^{\overline{b}} \leq p$, given $\underline{b} = \overline{b} = B^*$, it follows that $p_i(b_i^\varepsilon) = p_i^{B^*}(b_i^\varepsilon)$ for all $b_i^\varepsilon \neq B^*$ and all i (recall that for each player i one has $\Delta_i^\varepsilon(p_{-i}^{B^*} \mid B^*) = 0$, explaining the singleton exeption at $b_i^\varepsilon = B^*$). Thus, if $p = (p_i)$ is a BNE of G^ε then it must hold that $p_i(b_i^\varepsilon) = p_i^{B^*}(b_i^\varepsilon)$ for all $b_i^\varepsilon \neq B^*$ and all i, as I needed to prove. $\square$

Proposition 11 should not be misunderstood as saying that players will perfectly coordinate their actions (investments).[8] For $\varepsilon > 0$, it is possible that some players receive signals above B^* while others see a signal below it. When this occurs, players will fail to coordinate their actions (i.e. some will choose $x_i = 1$ while others choose $x_i = 0$). The implication is that empirically observed coordination failures are not necessarily at odds with, and therefore do not by themselves invalidate the model. When a coordination failure occurs, the equilibrium outcome is inefficient. In the limit as $\varepsilon \to 0$, the global climate game G^ε selects an essentially unique equilibrium of the underlying coordination game with multiple equilibria. To see this, note that for any $b > B^*$, I can find a $\varepsilon < B^* - b$ so that $b - \varepsilon > B^*$. Since $b_i^\varepsilon \in [b - \varepsilon, b + \varepsilon]$ and $p^* = p^{B^*}$ this implies that $p_i^*(b_i^\varepsilon) = 1$ for all b_i^ε consistent with b and all i.

[8]Perfect coordination of actions means that all players choose the same action.

Even as $\varepsilon \to 0$ and players coordinate their actions with probability 1, the unique equilibrium can be inefficient. In particular, players coordinate on $\mathbf{0}$ (all adopt the dirty technology) for all $b < B^*$ even though the outcome in which players coordinate on $\mathbf{1}$ (all adopt the clean technology) is Pareto strictly dominant for all $b > \bar{b}$ (and even though they know it). Since, $\bar{b} = (c(N) - d)/N$ so that clearly $\bar{b} < B^*$, it follows that for all b such that $\bar{b} < b < B^*$ coordination is on the Pareto dominated outcome of the underlying complete information game. Intuitively, clean investment will be too risky when b is low since the noise in signals forces a player to believe that others may think that clean investment is dominated. [15] appear to share this view when they write that "players could use risk-dominance as a selection rule." For 2×2 games, their statement is backed by the theoretical literature: Carlsson and Van Damme (1993) prove that any 2×2 global game selects the risk dominant equilibrium of the underlying true game.[9] In games with more players or actions, the statement is not generally correct. The result stands in contrast to the common and often implicit assumption in the environmental literature that players generally coordinate on the efficient equilibrium [13, 74].

Corollary 2. *(i) For all $b > B^* + \varepsilon$ it holds that* $\Pr\left[p^{B^**}(b^\varepsilon) = \mathbf{1}\right] = 1$. *(ii) For all $b < B^* - \varepsilon$ it holds that* $\Pr\left[p^{B^*}(b^\varepsilon) = \mathbf{0}\right] = 1$.

4.4 Network Subsidies

The potential of an inefficient outcome in both the game of complete information $G(b)$ and the global game G^ε begs the question how a policymaker can influence the game in order to reach an efficient outcome. In this section, I assume that there exists a policymaker who, using taxes and subsidies, has the ability to change the payoffs in the game; the players remain as assumed in Sections 4.2 and 4.3. I will study the policymaker's problem of finding a way to influence players' incentives so as to implement the Pareto efficient outcome of the game in strictly dominant strategies. That is, I seek to find policies that turn playing $x_i = 1$ into a strictly dominant strategy whenever coordination on $\mathbf{1}$ is also the efficient outcome of the game; similarly, I want $x_i = 0$ to be a strictly dominant strategy when coordination on $\mathbf{0}$ is Pareto efficient.[10] I assume that the policymaker is fully informed about players' possible

[9] For a definition of risk dominance, see [65].

[10] This question is related to the literature on mechanism design and (strictly dominant strategy) implementation. That is, I study the problem of a policymaker who seeks to change the original game studied in Section 4.2 and 4.3 with the aim of making coordination on the efficient outcome of the game a strictly dominant strategy for all players [94, 98, 116]. For applications of mechanism design and implementation theory to pollution problems like climate change, see [40], [8], and [103]. As an extension for future work directly related to the mechanism design literature, I hope to explicitly compare network subsidies the the well-studied Vicker-Clarke-Groves mechanism [such a comparison is also made in 8].

actions as well as the parameters of the model that are common knowledge among the players. I also assume that the policymaker understands players' payoff-maximization incentives. While in the most general setup, the policymaker has a vast array of possible policies at its disposal (including outright command-and-control), to stay close with the application to climate change I shall confine the set of feasible policies to subsidies and taxes only.

Taxes and subsidies will stimulate adoption of the clean technology whenever they cause an effective decrease of $c(m) - d$ for at least one m. The U.S. Federal Tax Credit for Solar Photovoltaics [22], California's Clean Vehicle Rebate Project [100], or the U.S. National Plug-In Electric Drive Vehicle Credit [32] are good illustrations. However, tax policies may not always be feasible, political or otherwise. For example, legislation on taxation requires unanimous agreement in the European Union, which is one reason the EU does not have a carbon tax. Subsidies and tax credits, on the other hand, come with a substantial budgetary burden. The Congressional Budget Office expects total cost from tax credits on electric vehicles to be about 7.5 billion U.S. dollars through 2019.[11] Planned spending on SDE++ subsidies in the Netherlands are 5 billion Euros in 2021.[12].

The expenditure on subsidies to stimulate clean technology adoption can be substantially mitigated without the need to compromise on efficiency through the use of *network subsidies*. A network subsidy, like any subsidy, is offered contingent on adoption of the clean technology. In contrast to a standard subsidy scheme, however, the amount of the subsidy upon adoption also depends on how many others adopt the clean technology, and is decreasing in that number.

Network subsidies provide a cheap yet effective policy instrument to stimulate the adoption of clean technologies. The literature on directed technical change has pointed out that there often exists a need for both taxes and subsidies in an efficient policy when the (clean) technologies exhibit positive external spillovers [2, 3, 62]. A policy of network subsidies might provide a relatively low-cost opportunity to direct technological change toward green technologies.

4.4.1 Game of Complete Information

Consider again the game of complete information (about b) discussed in Section 4.2. Recall from Proposition 8 that coordination on $x = \mathbf{1}$ is the Pareto strictly dominant outcome of the game for all $b > \bar{b}$, whereas coordination on $x = \mathbf{0}$ is efficient for all

[11] See https://www.cbo.gov/sites/default/files/112th-congress-2011-2012/reports/electricvehiclesone-col.pdf

[12] See https://www.rvo.nl/subsidie-en-financieringswijzer/sde. SDE is an acronym for Stimulering Duurzame Energievoorziening en Klimaattransitie, or "Stimulus Sustainable Energy Supply and Climate Transition".

$b < \bar{b}$.

My aim is to find a subsidy that incentivizes players to coordinate on the efficient outcome of the game for any b. Concretely, I want to formulate a tax and/or subsidy policy that makes $x_i = 1$ strictly dominant for all $b > \bar{b}$ while $x_i = 0$ becomes strictly dominant at $b < \bar{b}$. I say that such a subsidy *implements* the efficient outcome of the game in strictly dominant strategies for almost all b, i.e., for all b except $\bar{b}$.

First I will show that if $\mathbf{1}$ is a (strict) Nash equilibrium of $G(b)$, then the efficient outcome of the game can be implemented in (strictly) strictly dominant strategies at zero cost, even if $\mathbf{0}$ is also a strict Nash equilibrium. The idea will be to offer players choosing $x_i = 1$ a subsidy that guarantees them a payoff equal (when choosing 1) to what they would have realized in the hypothetical case that all other players also chose 1 – that is, to offer a subsidy that promises players a payoff as though they enjoyed the full extent of the network externality. To this end, let the policymaker offer a *network subsidy* $s^*(x)$ to each i choosing $x_i = 1$ when x is played. For each x, define $s^*(x)$ to be the function given by:

$$s^*(x) = \Delta_i(\mathbf{1}_{-i} \mid b) - \Delta_i(x_{-i} \mid b) = c(n(x)) - c(N). \tag{4.25}$$

Players choosing $x_i = 0$ do not receive a network subsidy. Observe that, conditional on $s^*(\cdot)$, an individual players' gain from playing 1, rather than 0, is:

$$\Delta_i(x_{-i} \mid b) + s^*(x) = \Delta_i(x_{-i} \mid b) + \Delta_i(\mathbf{1}_{-i} \mid b) - \Delta_i(x_{-i} \mid b) = \Delta_i(\mathbf{1}_{-i} \mid b), \tag{4.26}$$

for any x, confirming the claim that a network subsidy scheme $s^*(\cdot)$ allows players to consider only the gain $\Delta_i(\mathbf{1}_{-i} \mid b) = b - c(N) + d$ when choosing their actions.

Proposition 12. *Let $G(b \mid s^*)$ denote the game $G(b)$ in which players are offered the network subsidy $s^*(\cdot)$ on playing* 1.

(i) If $\mathbf{1}$ is a Nash equilibrium of $G(b)$ (i.e. if $b + d \geq c(N)$), then $\mathbf{1}$ is implemented in weakly dominant strategies with $s^*(\cdot)$ and no subsidies have to be paid.

(ii) If $\mathbf{1}$ is a strict Nash equilibrium of $G(b)$ (i.e. if $b + d > c(N)$), then $\mathbf{1}$ is implemented in strictly dominant strategies with $s^*(\cdot)$ and no subsidies have to be paid.

(iii) If $\mathbf{1}$ is not a Nash equilibrium of $G(b)$ (i.e. if $b + d < c(N)$), then $\mathbf{0}$ is implemented in strictly dominant strategies with $s^*(\cdot)$ and no subsidies have to be paid.

Proof. The gain from choosing $x_i = 1$ rather than $x_i = 0$, conditional on the network subsidy scheme $s^*(\cdot)$, given b and x_{-i} is (4.26) which, for all x_{-i}, is (strictly) positive if and only if $\mathbf{1}$ is a (strict) Nash equilibrium of the game. Thus, the offering a subsidy scheme equal to $s^*(\cdot)$ turns $x_i = 1$ into a (strictly) strictly dominant strategy whenever $\mathbf{1}$ is a (strict) Nash equilibrium of $G(b)$. When players coordinate on $\mathbf{1}$ total spending on network subsidies is $N \cdot s^*(\mathbf{1}) = 0$. □

Note that for all $b > c(N) - d$, and provided the network subsidy scheme $s^*(\cdot)$ is offered, the policymaker may even tax playing $x_i = 1$ yet still implement $\mathbf{1}$ in strictly dominant strategies.

Remark 1. *Let $b > c(N) - d$, so $\mathbf{1}$ is both a strict Nash equilibrium and the efficient outcome of the game $G(b)$. If the policymaker offers the network subsidy scheme $s^*(\cdot)$, the policymaker can impose a tax $t(b) \leq b + d - c(N)$ on playing $x_i = 1$ but nevertheless implement coordination on $\mathbf{1}$ in strictly dominant strategies.*

Proposition 12 tells us that a smart policy of network subsidies allows the policymaker costlessly to implement the efficient Nash equilibrium of $G(b)$ in (strictly) strictly dominant strategies if the game has multiple (strict) Nash equilibria. While this is a desirable property, it does not guarantee that a network subsidy scheme implements the efficient outcome of the game for all b. To see this, observe that $\mathbf{0}$ is the unique strict Nash equilibrium of $G(b)$ for all $b < c(N) - d$, while $\mathbf{1}$ is the efficient outcome for all $b > \bar{b} = (c(N) - d)/N$. Hence, if $c(N) > d$ the policymaker cannot implement the efficient outcome of the game for all $b \in (\bar{b}, c(N) - d)$ using a network subsidy scheme alone.

I next show that if $\mathbf{1}$ is not a Nash equilibrium of the game $G(b)$, but $\mathbf{1}$ is the efficient outcome, then in order to implement $\mathbf{1}$ in strictly dominant strategies, the policymaker can use a dual tax-subsidy scheme to achieve its goal. First, let the policymaker again offer the network subsidy scheme given by $s^*(\cdot)$. As I saw before, the net (accounting for subsidies) gain from playing 1 rather than 0 becomes $\Delta_i(x_{-i} \mid b) + s^*(x) = \Delta_i(\mathbf{1}_{-i} \mid b)$ when players are offered $s^*(\cdot)$. Second, let the policymaker levy an *environmental tax* $t(b)$ to playing 0. The purpose of the environmental tax is to make sure that $\Delta_i(\mathbf{1}_{-i} \mid b) + t(b) > 0$ for all $b > \bar{b}$ while $\Delta_i(\mathbf{1}_{-i} \mid b) + t(b) < 0$ for all $b < \bar{b}$; that is, the tax should make $\mathbf{1}$ a Nash equilibrium of the game if and only if $\mathbf{1}$ is also the efficient outcome; otherwise $\mathbf{0}$ should be the equilibrium. A tax $t(b)$ that achieves this is given by:

$$t(b) > \Delta(\mathbf{1}_{-i} \mid c(N) - d) - \Delta(\mathbf{1}_{-i} \mid b) = c(N) - d - b \quad \text{if} \quad b \geq \bar{b}, \tag{4.27}$$

while $t(b) = 0$ otherwise. It is easy to verify that $t(b)$ implements coordination on $\mathbf{1}$ as a strict Nash equilibrium for all $b > \bar{b}$ while leaving $x_i = 0$ strictly dominant for all $b < \bar{b}$.

Proposition 13. *Let $G(b \mid s^*, t)$ denote the game $G(b)$ in which the policymaker both offers the network subsidy scheme $s^*(\cdot)$ and levies the environmental tax $t(b)$. If $\mathbf{1}$ is* *not a Nash equilibrium of $G(b)$ (i.e. if $b < c(N) - d$), but* **1** *is the Pareto efficient outcome (i.e. $b > \bar{b}$), then, by taxing $x_i = 0$ through $t(b)$ while also offering a network subsidy $s^*(\cdot)$ to playing $x_i = 1$,* **1** *can be implemented in strictly dominant strategies at no cost (and tax revenues will be zero).*

Why does a network subsidy work so well despite the low cost? The key property of a network subsidy set at $s^*(\cdot)$ is that it eliminates all *strategic uncertainty*, i.e. the uncertainty a player has about the actions chosen by all other players. The network subsidy thus removes the payoff uncertainty deriving from strategic uncertainty interacted with technological spillovers – it turns the original coordination game into a simple dominance solvable game for all b. In so doing, the network subsidy manages to eliminate all inefficiencies caused by players' failure to internalize the *technological* spillovers inherent in clean investments. Intuitively, the network subsidy works like an insurance. It protects individual investors against the risk of small network externalities from clean investments in case many others have adopted the dirty technology. In so doing, it impels individuals toward clean investments. The network subsidy does not have to be paid as a result, being conditional on low investments by construction.

As I discussed in the introduction to this section, for various reasons governments across the globe may at times be reluctant to rely on (carbon) taxes when trying to curb private sector emissions. When this is true, the government cannot (or at least does not want to) levy the carbon tax $t(b)$ but may rather rely on an environmental *subsidy* $s(b)$ on playing 1.

Remark 2. *If* **1** *is not a Nash equilibrium of $G(b)$ (i.e. if $b < c(N) - d$), but* **1** *is the Pareto efficient outcome, then, by subsidizing $x_i = 1$ through $s(b) = c(N) - d - b$ while also offering a network subsidy $s(\cdot)$ to playing $x_i = 1$,* **1** *can be implemented in strictly dominant strategies. Total subsidy spending will be $N \cdot s(b)$ when $b > \bar{b}$, and zero otherwise.*

Note that a network subsidy differs from a Pigouvian subsidy on playing 1. A Pigouvian subsidy incentivizes each player to incorporate the effect his own choice of action has on the payoffs of all others; a network subsidy neutralizes the effect all other players' actions have on each individual player's choice of action.

4.4.2 Global Game

Consider the global game G^ε discussed in Section 4.3. In this game, players do not observe b but only some noisy private signal of it. I henceforth assume that the policymaker observes neither the true b nor a signal of it.

In this section I address the question of what tax-subsidy scheme suffices to implement the Pareto efficient outcome of the underlying game $G(b)$ in strictly dominant strategies for all b. I will assume the policymaker seeks policies that, for each player $i = 1, 2, .., N$, turn $x_i = 1$ into a strictly dominant action for all $b_i^\varepsilon > \bar{b}$ while leaving $x_i = 0$ strictly dominant for all $b_i^\varepsilon < \bar{b}$.[13] I will also assume that the policy scheme does not depend on the unobserved true b.[14].

First, let us again assume the policymaker offers each player a network subsidy s^* equal to:

$$s^*(x) = c(n(x)) - c(N), \tag{4.28}$$

which is the same network subsidy as in (4.25). It is easy to verify that the network subsidy $s^*(\cdot)$ makes playing 1 strictly dominant for all $b_i^\varepsilon > c(N) - d$. When players are offered $s^*(\cdot)$ for each x_{-i}, their expected gain (the expectation is over b) is:

$$\Delta_i^\varepsilon(x_{-i} \mid b_i^\varepsilon) + s^*(x) = \Delta_i^\varepsilon(\mathbf{1} \mid b_i^\varepsilon), \tag{4.29}$$

where $\Delta_i^\varepsilon(x_{-i} \mid b) := \frac{1}{2\varepsilon} \int_{b_i^\varepsilon - \varepsilon}^{b_i^\varepsilon + \varepsilon} \Delta(x_{-i} \mid b) db$. Note that $\Delta_i^\varepsilon(\mathbf{1} \mid b_i^\varepsilon)$ is strictly positive for all $b_i^\varepsilon > c(N) - d$ and strictly negative for all $b_i^\varepsilon < c(N) - d$. Let $G^\varepsilon(s^*)$ denote the global game G^ε in which the policymaker offers the network subsidy scheme $s^*(\cdot)$.

Lemma 3. *Consider the global game G^ε. Let the policymaker offer a network subsidy $s^*(\cdot)$ on playing 1. Then the action $x_i = 0$ is strictly dominant at $b_i^\varepsilon < c(N) - d$; the action $x_i = 1$ is strictly dominant at $b_i^\varepsilon > c(N) - d$.*

As in the case of complete information, a network subsidy alone may not suffice to implement the efficient outcome of the game; for all $b \in (\bar{b}, c(N) - d - \varepsilon)$, each player i receives a signal $b_i^\varepsilon < c(N) - d$ so playing 0 is strictly dominant despite the network subsidy. Therefore, let the policymaker – on top of the network subsidy – levy an environmental tax $\bar{t}$ on playing $x_i = 0$ that makes $x_i = 1$ strictly dominant, for all $b_i^\varepsilon > \bar{b}$ and all i, constrained by the condition that $x_i = 0$ should still be strictly dominant (despite both the subsidy and the tax) for all $b_i^\varepsilon < \bar{b}$. Thus, the policymaker wants to find a tax $\bar{t}$ (recall again the restrictive assumption that $\bar{t}$ does not depend on players' private knowledge of b) that solves:

$$\begin{aligned} \Delta_i^\varepsilon(x_{-i} \mid b_i^\varepsilon) + s^*(x) + \bar{t} = \Delta_i^\varepsilon(\mathbf{1} \mid b_i^\varepsilon) + \bar{t} > 0 \quad \text{for all} \quad b_i^\varepsilon > \bar{b} \\ \Delta_i^\varepsilon(x_{-i} \mid b_i^\varepsilon) + s^*(x) + \bar{t} = \Delta_i^\varepsilon(\mathbf{1} \mid b_i^\varepsilon) + \bar{t} < 0 \quad \text{for all} \quad b_i^\varepsilon < \bar{b}, \end{aligned} \tag{4.30}$$

[13] I use the word "leaving" because in the global game G^ε *without* policy intervention, playing $x_i = 0$ is already strictly dominant for all i and all $b_i^\varepsilon < \bar{b} < B^*$.

[14] To be more precise, I assume that the only observables on which the policy scheme depends are players' actions. This is a restrictive assumption. Players possess private information (their signals) about b and this information is correlated. We thus know from the literature on mechanism design that the policymaker can (costlessly) extract the vector of signals $b^\varepsilon = (b_1^\varepsilon, b_2^\varepsilon, ..., b_N^\varepsilon)$ from the players [33, 106]. Especially when ε is small, knowing b^ε would provide an almost perfect signal of the true b to the policymaker. It seems intuitive that the policymaker might use this knowledge to its benefit (and the benefit of all players as a whole). I hope to investigate this issue – including a direct comparison between a network subsidy and the Vickrey–Clarke–Groves mechanism – in future work.

for all i and all x_{-i}. It follows that $\bar{t}$ is given by:

$$\bar{t} = (N-1)\cdot\bar{b} = (N-1)\cdot\frac{c(N)-d}{N}. \tag{4.31}$$

Let $G^{\varepsilon}(s^*, \bar{t})$ denote the global game G^{ε} in which the policymaker both offers the network subsidy scheme $s^*(\cdot)$ and levies an environmental tax $\bar{t}$. The following result regarding $G^{\varepsilon}(s^*, \bar{t})$ is immediate.

Proposition 14. *Consider the global game $G^{\varepsilon}(s^*, \bar{t})$. If the policymaker offers a network subsidy $s^*(\cdot)$ on playing $x_i = 1$ and levies a tax $\bar{t}$ on playing $x_i = 0$, then, for each player i, the action $x_i = 0$ is strictly dominant for all $b_i^{\varepsilon} < \bar{b}$ and the action $x_i = 1$ is strictly dominant for all $b_i^{\varepsilon} > \bar{b}$. Hence, for all $b \notin [\bar{b}-\varepsilon, \bar{b}+\varepsilon]$ the policymaker can implement the efficient outcome of the game $G(b)$ in strictly dominant actions at no cost.*

Proof. Strict dominance is an immediate consequence of rewriting the player i's gain including taxes and subsidies:

$$\Delta_i^{\varepsilon}(x_{-i} \mid b_i^{\varepsilon}) + s^*(x) + \bar{t} = \Delta_i^{\varepsilon}(\mathbf{1} \mid b_i^{\varepsilon}) + \bar{t} = b_i^{\varepsilon} + c(N) - d + (N-1)\cdot\frac{c(N)-d}{N}, \tag{4.32}$$

which is strictly positive for all $b_i^{\varepsilon} > \bar{b}$ and strictly negative for all $b_i^{\varepsilon} < \bar{b}$. As to the final claim in the Proposition, observe that each b_i^{ε} is drawn from $[b-\varepsilon, b+\varepsilon]$, given b. Hence, if $b > \bar{b}+\varepsilon$ then $b_i^{\varepsilon} > \bar{b}$ for each i, so playing $x_i = 1$ is strictly dominant and players coordinate on $\mathbf{1}$, the efficient outcome of the game (for those b). In this case, total spending on subsidies is $s^*(\mathbf{1}) = 0$. Similarly, if $b < \bar{b}-\varepsilon$ then $b_i^{\varepsilon} < \bar{b}$ for each i, so playing $x_i = 0$ is strictly dominant and players coordinate on $\mathbf{0}$, the efficient outcome of the game (for those b). Since no player plays 1, total subsidy spending is naturally zero. $\square$

If the policymaker, for whatever reason, is reluctant to tax playing 0, it may also offer both a network subsidy $s^*(\cdot)$ together with an environmental *subsidy* equal to $\bar{t}$ to playing 1. Such a policy is evidently equivalent with regard to players' incentives, although it differs for the policymaker's budget.

Corollary 3. *Consider the global game G^{ε}. Let the policymaker offer a network subsidy $s^*(\cdot)$ on playing 1. In addition, let the policymaker offer an environmental subsidy (rather than a tax) equal to $\bar{t}$ on playing 1. Then the action $x_i = 0$ is strictly dominant for all $b_i^{\varepsilon} < \bar{b}$ while the action $x_i = 1$ is strictly dominant for all $b_i^{\varepsilon} > \bar{b}$. Hence, the policymaker can implement the efficient outcome of the game $G(b)$ for all $b \notin [\bar{b}-\varepsilon, \bar{b}+\varepsilon]$; total subsidy spending is $N\cdot\bar{b}$ if $b > \bar{b}+\varepsilon$ and 0 if $b < \bar{b}-\varepsilon$.*

If a true b in $(\bar{b}-\varepsilon, \bar{b}+\varepsilon)$ is drawn, players may fail to coordinate on either **0** or **1** even when the policymaker offers the network subsidy $s^*(\cdot)$ and levies the tax $\bar{t}$. The reason is that, for those b, players' signals need not all fall in the strict dominance regions identified in Proposition 14, and a coordination failure may easily arise. The network subsidy scheme $s^*(\cdot)$ may hence not be costless; for any x not equal to **0** or **1**, total spending on network subsidies will be $n(x) \cdot s^*(x) > 0$. Thus, the remarkably strong performance of a network subsidy scheme may break down in the global game. For $\varepsilon > 0$, the event that a true b in $(\bar{b}-\varepsilon, \bar{b}+\varepsilon)$ is drawn occurs with strictly positive probability, namely $2\varepsilon/(\overline{B}-\underline{B}) > 0$. Only in the limit as $\varepsilon \to 0$ will this problem disappear: players perfectly coordinate their actions (in equilibrium) save for the probability-zero event that $b = \bar{b}$.

The fact that spending on network subsidies may not be zero in the global game is unfortunate. To remedy this problem, I now derive a network tax-subsidy scheme where subsidy payments on $x_i = 1$ are financed through a "network tax" levied on choosing $x_i = 0$.[15] Let the subsidy be denoted $s^{**}(x)$; the corresponding tax is denoted $t^{**}(x)$. Thus, when x is played, aggregate spending on network subsidies is $n(x) \cdot s^{**}(x)$; aggregate revenues from the network tax are $(N - n(x)) \cdot t^{**}(x)$. If I want the tax-subsidy scheme to be costless, or self-financed, the budget constraint for this scheme is given by:

$$(N - n(x)) \cdot t^{**}(x) - n(x) \cdot s^{**}(x) = 0, \tag{4.33}$$

which should hold for all x. Condition (4.33) imposes that total spending on the network subsidies to those playing 1 is matched exactly by total tax revenues from taxing those who play 0, whatever players end up playing.

Next, the tax-subsidy scheme, together with the environmental tax $\bar{t}$ given by (4.31), must make $x_i = 1$ strictly dominant for all $b_i^\varepsilon > \bar{b}$ while leaving $x_i = 0$ strictly dominant for all $b_i^\varepsilon < \bar{b}$. Thus players' gains from playing 1, rather than 0, accounting for taxes and subsidies, should satisfy:

$$\Delta_i^\varepsilon(x_{-i} \mid b_i^\varepsilon) + \bar{t} + s^{**}(x) + t^{**}(x) > 0 \quad \text{for all} \quad b_i^\varepsilon > \bar{b}, \tag{4.34}$$

$$\Delta_i^\varepsilon(x_{-i} \mid b_i^\varepsilon) + \bar{t} + s^{**}(x) + t^{**}(x) < 0 \quad \text{for all} \quad b_i^\varepsilon < \bar{b}, \tag{4.35}$$

for all i and all x_{-i}. Equations (4.34) and (4.35) represent the incentive constraints of a network tax-subsidy scheme. Combined with the budget constraint, this yields

[15] An alternative approach to this problem would be to let the policymaker extract players' private signals (see footnote 14) and then construct a policy scheme such that, when the signals indicate a high b, the policymaker may tax playing 1 similarly to the way discussed in Remark 1. The policymaker could then construct this policy in such a way that ex ante, i.e. before b is drawn, the policy scheme has expected cost zero. This is different from the present analysis, which is more demanding and imposes ex post budget neutrality.

the following network tax-subsidy scheme (s^{**}, t^{**}):

$$\begin{cases} t^{**}(x) = & \frac{n(x)}{N}\left[c(n(x)) - c(N)\right] \\ s^{**}(x) = & \frac{N-n(x)}{N}\left[c(n(x)) - c(N)\right] \end{cases} \tag{4.36}$$

The policy scheme $((s^{**}, t^{**}), \bar{t})$ can now be summarized as follows. When x is played and player i has played 1 in x, s/he receives a network subsidy equal to $s^{**}(x)$; however, if player i played 0 in x, s/he pays a tax equal to $\bar{t} + t^{**}(x)$. Let $G^{\varepsilon}((s^{**}, t^{**}), \bar{t})$ denote the global game G^{ε} in which the policymaker both offers the network subsidy scheme $s^{*}(\cdot)$ and levies an environmental tax $\bar{t}$.

Proposition 15. *Consider the global game $G^{\varepsilon}((s^{**}, t^{**}), \bar{t})$. Let the policymaker offer a network subsidy equal to $s^{**}(\cdot)$ on playing 1 while levying a tax equal to $\bar{t} + t^{**}(\cdot)$ on playing 0. This policy makes the action $x_i = 0$ strictly dominant for all $b_i^{\varepsilon} < \bar{b}$; the action $x_i = 1$ is strictly dominant for all $b_i^{\varepsilon} > \bar{b}$. Consequently, the policymaker can implement efficient outcome of the game $G(b)$ for all $b \notin [\bar{b} - \varepsilon, \bar{b} + \varepsilon]$; net spending on the policy scheme $((s^{**}, t^{**}), \bar{t})$ is zero for all b.*

Proof. All parts of the propositions follow immediately from the construction preceding it. □

The present analysis did not make use of the fact that, without policy interventions, playing p^{B^*} is the essentially unique strategy profile surviving iterated dominance in the global game G^{ε}. Another approach toward ((iterative) strictly dominant strategy) implementation in G^{ε} would be to study what mechanisms the policymaker could design to shift the threshold B^* down toward $\bar{b}$. I intend to do this in future work.

Finally, observe that the logic of a network subsidy does not rely on the application to climate change. Any market where (i) individual actions exhibit strategic complementarities and (ii) players do not take these into account may coordinate on an inefficient equilibrium. A network subsidy then offers an inexpensive way out of this trap. The observation suggests that network subsidies are worth studying in economics more generally.

4.5 Summary

This paper studies climate change mitigation in a global game. I focus on abatement through technological investment. Players invest in either of two technologies. One technology is cheap and dirty, the other expensive but clean. I consider the coordination problem inherent in players' decisions; that is, I focus on environments in which investments are strategic complements. These could for example arise due to network effects, technological spillovers, or learning-by-doing. Consistent with the existing literature on technological investments in clean technologies, I demonstrate that the complete information version of my game has multiple equilibria [13, 15, 17, 74, 110]. Equilibrium multiplicity can lead to coordination failure and complicates the design of domestic policies or climate treaties.

To this well-studied framework, I add a little bit of uncertainty. I assume that the true environmental benefit of the clean technology is unobserved. Rather than observe the technology's true benefit, players receive private noisy signals of it. In this *global climate game*, I show that there exists a unique equilibrium in which players adopt the clean technology if and only if their private signals exceed an endogenous threshold. For signals below the threshold, players adopt the dirty technology instead.

My first contribution is to show that the game has an essentially unique Bayesian Nah equilibrium. This contribution directly addresses the issue of equilibrium multiplicity often encountered in this literature. Equilibrium selection is driven by the assumption of incomplete information, which seems realistic in the context of clean technologies and climate change. The derivation of an essentially unique equilibrium connects this paper to the substantially more general literature on global games [31, 51]. The analysis highlights that the precise way in which one models uncertainty is important. Although some papers conclude that "shared" uncertainty does not eliminate equilibrium multiplicity in coordination games [14, 15], this paper shows the starkly contrasting result that privately held beliefs about the shared game does force selection of a unique equilibrium. The assumed structure of uncertainty matters. My result motivates a critical approach toward the modeling of uncertainty in environmental economics.

My second contribution is to introduce network subsidies. The issue of policy arises naturally in the present context where investments cause two externalities. One is an environmental externality that derives from the positive environmental effect clean investments have on all players; the other is a network externality deriving from spillovers (strategic complementarities) in clean investments. As I show, using only taxes and subsidies the policymaker can costlessly correct both of these externalities by turning the (expected) efficient action into a strictly dominant action for all players (both in the game of complete information and in the global game). Moreover, I also show that even when using only subsidies, the policymaker can correct the entire network externality at zero cost. The innovation here is what I call a network subsidy. Like standard subsidies, a network subsidy offers adopters of the clean technology a (financial) reward. In contrast to a standard subsidy scheme, however, the amount of the subsidy upon adoption also depends on how many others adopt the clean technology, and is decreasing in that number. As I show, it is possible to construct a simple network subsidy scheme that corrects the entire network externality deriving from players' ignorance of the technological spillovers caused by their clean investment but does not, in equilibrium, cost the policymaker anything. Intuitively, the network subsidy serves as an insurance against small clean technology networks. In so doing, it boosts clean investments and therefore is never claimed. Although derived in the context of technological spillovers, the notion of a network subsidy is general and applies to public economic broadly.

My derivation of network subsidies can be considered a restrictive yet simple exercise in mechanism design or implementation theory. While mechanism design has been applied to environmental economics and, in particular, emissions mitigation before [8, 40, 103], these papers tend to construct mechanisms that solve the free-rider problem. In this paper, I instead derive a mechanism to overcome the coordination problem. My approach is therefore complementary to these earlier constributions.

The results in this paper are derived under very strong assumptions regarding functional forms, the distribution of noise, the policymaker's knowledge, and timing. While results due to [51] suggest that equilibrium selection continues to occur in far more general global coordination games, none of these generalizations are investigated here. The intuition behind the cost-effectiveness of network subsidies would also seem to generalize; such generalizations, too, have not been investigated. Similarly, I assumed that the policymakers knows all parameters of the model known to the players; it is not clear how to design a network subsidy scheme (and what its properties would be) if the policymaker knows less. Finally, I study a static game in which decisions are taken only once. In relevant real-world cases, technology adoption and policy are inherently dynamic; this is a very restrictive simplification which I hope to relax in future work.

Bibliography

[1] Abrell, J. and Rausch, S. (2017). Combining price and quantity controls under partitioned environmental regulation. *Journal of Public Economics*, 145:226–242.

[2] Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *American economic review*, 102(1):131–66.

[3] Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51.

[4] Aghion, P. and Jaravel, X. (2015). Knowledge spillovers, innovation and growth. *The Economic Journal*, 125(583):533–573.

[5] Aldy, J. E., Krupnick, A. J., Newell, R. G., Parry, I. W., and Pizer, W. A. (2010). Designing climate mitigation policy. *Journal of Economic Literature*, 48(4):903–34.

[6] Allcott, H. (2011). Social norms and energy conservation. *Journal of public Economics*, 95(9-10):1082–1095.

[7] Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, 458(7242):1163–1166.

[8] Ambec, S. and Ehlers, L. (2016). Regulation via the polluter-pays principle. *The Economic Journal*, 126(593):884–906.

[9] Andor, M. A., Gerster, A., Peters, J., and Schmidt, C. M. (2020). Social norms and energy conservation beyond the us. *Journal of Environmental Economics and Management*, 103:102351.

[10] Antoniou, F. and Kyriakopoulou, E. (2019). On the strategic effect of international permits trading on local pollution. *Environmental and Resource Economics*, 74(3):1299–1329.

[11] Auerbach, A. J. and Gorodnichenko, Y. (2012). Measuring the output responses to fiscal policy. *American Economic Journal: Economic Policy*, 4(2):1–27.

[12] Aumann, R. J. (1976). Agreeing to disagree. *The annals of statistics*, pages 1236–1239.

[13] Barrett, S. (2006). Climate treaties and "breakthrough" technologies. *American Economic Review*, 96(2):22–25.

[14] Barrett, S. (2013). Climate treaties and approaching catastrophes. *Journal of Environmental Economics and Management*, 66(2):235–250.

[15] Barrett, S. and Dannenberg, A. (2012). Climate negotiations under scientific uncertainty. *Proceedings of the National Academy of Sciences*, 109(43):17372–17376.

[16] Barrett, S. and Dannenberg, A. (2014). Sensitivity of collective action to uncertainty about climate tipping points. *Nature Climate Change*, 4(1):36–39.

[17] Barrett, S. and Dannenberg, A. (2017). Tipping versus cooperating to supply a public good. *Journal of the European Economic Association*, 15(4):910–941.

[18] Battaglini, M. and Harstad, B. (2016). Participation and duration of environmental agreements. *Journal of Political Economy*, 124(1):160–204.

[19] Bauer, N., McGlade, C., Hilaire, J., and Ekins, P. (2018). Divestment prevails over the green paradox when anticipating strong future climate policies. *Nature Climate Change*, 8(2):130.

[20] Böhringer, C., Rosendahl, K. E., and Storrøsten, H. B. (2017). Robust policies to mitigate carbon leakage. *Journal of Public Economics*, 149:35–46.

[21] Boleslavsky, R. and Kelly, D. L. (2014). Dynamic regulation design without payments: The importance of timing. *Journal of Public Economics*, 120:169–180.

[22] Borenstein, S. (2017). Private net benefits of residential solar pv: The role of electricity tariffs, tax incentives, and rebates. *Journal of the Association of Environmental and Resource Economists*, 4(S1):S85–S122.

[23] Borenstein, S., Bushnell, J., Wolak, F. A., and Zaragoza-Watkins, M. (2019). Expecting the unexpected: Emissions uncertainty and environmental market design. *American Economic Review*, 109(11):3953–77.

[24] Bruninx, K., Ovaere, M., and Delarue, E. (2020). The long-term impact of the Market Stability Reserve on the EU Emission Trading System. *Energy Economics*, 89:104746.

[25] Bulow, J. I., Geanakoplos, J. D., and Klemperer, P. D. (1985). Multimarket oligopoly: Strategic substitutes and complements. *Journal of Political economy*, 93(3):488–511.

[26] Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239.

[27] Bushnell, J. B., Chong, H., and Mansur, E. T. (2013). Profiting from regulation: Evidence from the European carbon market. *American Economic Journal: Economic Policy*, 5(4):78–106.

[28] Calzolari, G., Casari, M., and Ghidoni, R. (2018). Carbon is forever: A climate change experiment on cooperation. *Journal of environmental economics and management*, 92:169–184.

[29] Caplan, A. J. and Silva, E. C. (2005). An efficient mechanism to control correlated externalities: redistributive transfers and the coexistence of regional and global pollution permit markets. *Journal of Environmental Economics and Management*, 49(1):68–82.

[30] Carbone, J. C., Helm, C., and Rutherford, T. F. (2009). The case for international emission trade in the absence of cooperative climate policy. *Journal of Environmental Economics and Management*, 58(3):266–280.

[31] Carlsson, H. and Van Damme, E. (1993). Global games and equilibrium selection. *Econometrica*, pages 989–1018.

[32] Clinton, B. C. and Steinberg, D. C. (2019). Providing the spark: Impact of financial

incentives on battery electric vehicle adoption. *Journal of Environmental Economics and Management*, 98:102255.

[33] Crémer, J. and McLean, R. P. (1988). Full extraction of the surplus in bayesian and dominant strategy auctions. *Econometrica: Journal of the Econometric Society*, pages 1247–1257.

[34] Dasgupta, P., Hammond, P., and Maskin, E. (1980). On imperfect information and optimal pollution control. *The Review of Economic Studies*, 47(5):857–860.

[35] De Coninck, H., Fischer, C., Newell, R. G., and Ueno, T. (2008). International technology-oriented agreements to address climate change. *Energy Policy*, 36(1):335–356.

[36] Dengler, S., Gerlagh, R., Trautmann, S. T., and Van De Kuilen, G. (2018). Climate policy commitment devices. *Journal of Environmental Economics and Management*, 92:331–343.

[37] Dietz, S. and Stern, N. (2015). Endogenous growth, convexity of damage and climate risk: how nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, 125(583):574–620.

[38] Doda, B., Quemin, S., and Taschini, L. (2019). Linking permit markets multilaterally. *Journal of Environmental Economics and Management*, 98:102259.

[39] Doda, B. and Taschini, L. (2017). Carbon dating: When is it beneficial to link etss? *Journal of the Association of Environmental and Resource Economists*, 4(3):701–730.

[40] Duggan, J. and Roberts, J. (2002). Implementing the efficient allocation of pollution. *American Economic Review*, 92(4):1070–1078.

[41] EU (2019). Communication from the commission. publication of the total number of allowances in circulation in 2018 for the purposes of the market stability reserve under the eu emissions trading system established by directive 2003/87/ec. Technical report, https://ec.europa.eu/clima/sites/clima/files/ets/reform/docs/c_2019_3288_en.pdf.

[42] EU Commission (2019). Communication on the european green deal. https://ec.europa.eu/info/publications/communication-european-green-deal_en.

[43] Fabra, N. and Reguant, M. (2014). Pass-through of emissions costs in electricity markets. *American Economic Review*, 104(9):2872–99.

[44] Fell, H. (2016). Comparing policies to confront permit over-allocation. *Journal of Environmental Economics and Management*, 80:53–68.

[45] Fell, H., MacKenzie, I. A., and Pizer, W. A. (2012). Prices versus quantities versus bankable quantities. *Resource and Energy Economics*, 34(4):607–623.

[46] Fischer, C. and Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of environmental economics and management*, 55(2):142–162.

[47] Flachsland, C., Marschinski, R., and Edenhofer, O. (2009a). Global trading versus linking: Architectures for international emissions trading. *Energy Policy*, 37(5):1637–1647.

[48] Flachsland, C., Marschinski, R., and Edenhofer, O. (2009b). To link or not to link: benefits and disadvantages of linking cap-and-trade systems. *Climate Policy*, 9(4):358–372.

[49] Flachsland, C., Pahle, M., Burtraw, D., Edenhofer, O., Elkerbout, M., Fischer, C., Tietjen, O., and Zetterberg, L. (2020). How to avoid history repeating itself: the

case for an eu emissions trading system (eu ets) price floor revisited. *Climate Policy*, 20(1):133–142.

[50] Fowlie, M., Reguant, M., and Ryan, S. P. (2016). Market-based emissions regulation and industry dynamics. *Journal of Political Economy*, 124(1):249–302.

[51] Frankel, D. M., Morris, S., and Pauzner, A. (2003). Equilibrium selection in global games with strategic complementarities. *Journal of Economic Theory*, 108(1):1–44.

[52] Gerlagh, R. (2011). Too much oil. *CESifo Economic Studies*, 57(1):79–102.

[53] Gerlagh, R. and Heijmans, R. (2020). Regulating stock externalities.

[54] Gerlagh, R., Heijmans, R., and Rosendahl, K. E. (2020a). COVID-19 tests the Market Stability Reserve. *Environmental and Resource Economics*, forthcoming.

[55] Gerlagh, R. and Heijmans, R. J. (2019a). Climate-conscious consumers and the buy, bank, burn program. *Nature Climate Change*, 9(6):431–433.

[56] Gerlagh, R., Heijmans, R. J., and Rosendahl, K. E. (2020b). COVID-19 tests the market stability reserve. *Environmental and Resource Economics*, 76(4):855–865.

[57] Gerlagh, R., Heijmans, R. J., and Rosendahl, K. E. (2021). An endogenous emission cap produces a green paradox. *Economic Policy*.

[58] Gerlagh, R. and Heijmans, R. J. R. K. (2019b). Climate-conscious consumers and the buy, bank, burn program. *Nature Climate Change*.

[59] Gillingham, K. and Tsvetanov, T. (2019). Hurdles and steps: Estimating demand for solar photovoltaics. *Quantitative Economics*, 10(1):275–310.

[60] Gollier, C., Jullien, B., and Treich, N. (2000). Scientific progress and irreversibility: an economic interpretation of the 'precautionary principle'. *Journal of Public Economics*, 75(2):229–253.

[61] Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

[62] Greaker, M., Heggedal, T.-R., and Rosendahl, K. E. (2018). Environmental policy and the direction of technical change. *The Scandinavian Journal of Economics*, 120(4):1100–1138.

[63] Greaker, M. and Midttømme, K. (2016). Network effects and environmental externalities: Do clean technologies suffer from excess inertia? *Journal of Public Economics*, 143:27–38.

[64] Habla, W. and Winkler, R. (2018). Strategic delegation and international permit markets: Why linking may fail. *Journal of environmental economics and management*, 92:244–250.

[65] Harsanyi, J. C. and Selten, R. (1988). A general theory of equilibrium selection in games. *MIT Press*.

[66] Harstad, B. (2012). Climate contracts: A game of emissions, investments, negotiations, and renegotiations. *Review of Economic Studies*, 79(4):1527–1557.

[67] Harstad, B. (2016). The dynamics of climate agreements. *Journal of the European Economic Association*, 14(3):719–752.

[68] Harstad, B. and Eskeland, G. S. (2010). Trading for the future: Signaling in permit markets. *Journal of public economics*, 94(9-10):749–760.

[69] Harstad, B., Lancia, F., and Russo, A. (2019). Compliance technology and self-enforcing agreements. *Journal of the European Economic Association*, 17(1):1–29.

[70] Hasegawa, M. and Salant, S. (2014). Cap-and-trade programs under delayed compliance: Consequences of interim injections of permits. *Journal of Public Economics*, 119:24–34.

[71] Heutel, G. (2020). Bankability and information in pollution policy. *Journal of the Association of Environmental and Resource Economists*, 7(4):779–799.

[72] Hintermann, B., Peterson, S., and Rickels, W. (2016). Price and market behavior in Phase II of the EU ETS: A review of the literature. *Review of Environmental Economics and Policy*, 10(1):108–128.

[73] Hintermayer, M. (2020). A carbon price floor in the reformed EU ETS: Design matters! *Energy Policy*, 147:111905.

[74] Hoel, M. and de Zeeuw, A. (2010). Can a focus on breakthrough technologies improve the performance of international environmental agreements? *Environmental and Resource Economics*, 47(3):395–406.

[75] Hoel, M. and Karp, L. (2001). Taxes and quotas for a stock pollutant with multiplicative uncertainty. *Journal of Public Economics*, 82(1):91–114.

[76] Holland, S. P. and Yates, A. J. (2015). Optimal trading ratios for pollution permit markets. *Journal of Public Economics*, 125:16–27.

[77] Holt, C. A. and Shobe, W. M. (2016). Reprint of: Price and quantity collars for stabilizing emission allowance prices: Laboratory experiments on the eu ets market stability reserve. *Journal of Environmental Economics and Management*, 80:69–86.

[78] Holtsmark, B. and Weitzman, M. L. (2020). On the effects of linking cap-and-trade systems for CO2 emissions. *Environmental and Resource Economics*, 75(3):615–630.

[79] Holtsmark, K. and Midttømme, K. (2021). The dynamics of linking permit markets. *Journal of Public Economics*, 198:104406.

[80] Hong, F. and Karp, L. (2012). International environmental agreements with mixed strategies and investment. *Journal of Public Economics*, 96(9-10):685–697.

[81] Hornsey, M. J., Harris, E. A., Bain, P. G., and Fielding, K. S. (2016). Meta-analyses of the determinants and outcomes of belief in climate change. *Nature climate change*, 6(6):622–626.

[82] Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy*, 39(2):137–175.

[83] ICAP (2020). Icap brief 3: Emissions trading at a glance. *International Carbon Action Partnership*.

[84] Kandori, M., Mailath, G. J., and Rob, R. (1993). Learning, mutation, and long run equilibria in games. *Econometrica: Journal of the Econometric Society*, pages 29–56.

[85] Karp, L. and Traeger, C. (2017). Smart cap. *Paper presented at the CESifo Energy and Climate Economics Conference, Munich, October 2017.*

[86] Karp, L. and Traeger, C. (2018). Prices versus quantities reassessed. *Paper presented at the CESifo Energy and Climate Economics Conference, Munich, October 2018*.

[87] Karp, L. and Traeger, C. P. (2021). Smart cap.

[88] Katz, M. L. and Shapiro, C. (1985). Network externalities, competition, and compatibility. *American Economic Review*, 75(3):424–440.

[89] Kling, C. and Rubin, J. (1997). Bankable permits for the control of environmental pollution. *Journal of Public Economics*, 64(1):101–115.

[90] Kollenberg, S. and Taschini, L. (2019). Dynamic supply adjustment and banking under uncertainty in an emission trading scheme: the market stability reserve. *European Economic Review*.

[91] Kolstad, C. D. (1996). Fundamental irreversibilities in stock externalities. *Journal of Public Economics*, 60(2):221–233.

[92] Kolstad, C. D. (2007). Systematic uncertainty in self-enforcing international environmental agreements. *Journal of Environmental Economics and Management*, 53(1):68–79.

[93] Kotchen, M. J. (2018). Which social cost of carbon? A theoretical perspective. *Journal of the Association of Environmental and Resource Economists*, 5(3):673–694.

[94] Kuzmics, C. and Steg, J.-H. (2017). On public good provision mechanisms with dominant strategies and balanced budget. *Journal of Economic Theory*, 170:56–69.

[95] Kverndokk, S., Figenbaum, E., and Hovi, J. (2020). Would my driving pattern change if my neighbor were to buy an emission-free car? *Resource and Energy Economics*, 60:101153.

[96] Kverndokk, S. and Rosendahl, K. E. (2007). Climate policies and learning by doing: Impacts and timing of technology subsidies. *Resource and Energy Economics*, 29(1):58–82.

[97] Kwerel, E. (1977). To tell the truth: Imperfect information and optimal pollution control. *The Review of Economic Studies*, 44(3):595–601.

[98] Laffont, J.-J. and Maskin, E. (1982). Nash and dominant strategy implementation in economic environments. *Journal of Mathematical Economics*, 10(1):17–47.

[99] Leroux, J. and Spiro, D. (2018). Leading the unwilling: Unilateral strategies to prevent arctic oil exploration. *Resource and Energy Economics*, 54:125–149.

[100] Li, S., Tong, L., Xing, J., and Zhou, Y. (2017). The market for electric vehicles: indirect network effects and policy design. *Journal of the Association of Environmental and Resource Economists*, 4(1):89–133.

[101] Lintunen, J. and Kuusela, O.-P. (2018). Business cycles and emission trading with banking. *European Economic Review*, 101:397–417.

[102] Makris, M. (2008). Complementarities and macroeconomics: Poisson games. *Games and Economic Behavior*, 62(1):180–189.

[103] Martimort, D. and Sand-Zantman, W. (2016). A mechanism design approach to climate-change agreements. *Journal of the European Economic Association*, 14(3):669–718.

[104] Martin, R., Muûls, M., De Preux, L. B., and Wagner, U. J. (2014). Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme. *American Economic Review*, 104(8):2482–2508.

[105] Matsui, A. and Matsuyama, K. (1995). An approach to equilibrium selection. *Journal of Economic Theory*, 65(2):415–434.

[106] McAfee, R. P. and Reny, P. J. (1992). Correlated information and mecanism design. *Econometrica: Journal of the Econometric Society*, pages 395–421.

[107] Mehling, M. A., Metcalf, G. E., and Stavins, R. N. (2018). Linking climate policies to advance global mitigation. *Science*, 359(6379):997–998.

[108] Mertens, K. and Ravn, M. O. (2012). Empirical evidence on the aggregate effects of anticipated and unanticipated US tax policy shocks. *American Economic Journal: Economic Policy*, 4(2):145–81.

[109] Mideksa, T. K. and Weitzman, M. L. (2019). Prices versus quantities across jurisdictions. *Journal of the Association of Environmental and Resource Economists*, 6(5):883–891.

[110] Mielke, J. and Steudle, G. A. (2018). Green investment and coordination failure: An investors' perspective. *Ecological Economics*, 150:88–95.

[111] Monderer, D. and Shapley, L. S. (1996). Potential games. *Games and economic behavior*, 14(1):124–143.

[112] Montgomery, W. D. (1972). Markets in licenses and efficient pollution control programs. *Journal of Economic Theory*, 5(3):395–418.

[113] Morris, S. and Shin, H. S. (1998). Unique equilibrium in a model of self-fulfilling currency attacks. *American Economic Review*, pages 587–597.

[114] Myerson, R. B. (1998). Population uncertainty and poisson games. *International Journal of Game Theory*, 27(3):375–392.

[115] Myerson, R. B. (2000). Large poisson games. *Journal of Economic Theory*, 94(1):7–45.

[116] Myerson, R. B. and Satterthwaite, M. A. (1983). Efficient mechanisms for bilateral trading. *Journal of economic theory*, 29(2):265–281.

[117] Newell, R., Pizer, W., and Zhang, J. (2005). Managing permit markets to stabilize prices. *Environmental and Resource Economics*, 31(2):133–157.

[118] Newell, R. G. and Pizer, W. A. (2003). Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management*, 45(2):416–432.

[119] Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, 105(4):1339–70.

[120] Nyborg, K. (2018a). Reciprocal climate negotiators. *Journal of Environmental Economics and Management*, 92:707–725.

[121] Nyborg, K. (2018b). Social norms and the environment. *Annual Review of Resource Economics*.

[122] Nyborg, K., Howarth, R. B., and Brekke, K. A. (2006). Green consumers and public policy: On socially contingent moral motivation. *Resource and energy economics*, 28(4):351–366.

[123] Osborne, M. J. and Rubinstein, A. (1994). *A course in game theory*. MIT press.

[124] Perino, G. (2018). New eu ets phase 4 rules temporarily puncture waterbed. *Nature Climate Change*, 8(4):262.

[125] Perino, G. and Willner, M. (2016). Procrastinating reform: The impact of the market stability reserve on the eu ets. *Journal of Environmental Economics and Management*, 80:37–52.

[126] Perino, G. and Willner, M. (2017). EU-ETS Phase IV: Allowance prices, design choices, and the Market Stability Reserve. *Climate Policy*, 17:936–946.

[127] Pizer, W. A. (2002). Combining price and quantity controls to mitigate global climate change. *Journal of public economics*, 85(3):409–434.

[128] Pizer, W. A. and Prest, B. C. (2020). Prices versus quantities with policy updating. *Journal of the Association of Environmental and Resource Economists*, 7(3):483–518.

[129] RefinitivCarbon (2018). Eua price forecast: A new era for european carbon or calmer waters ahead? Technical report, Refinitiv.

[130] Roberts, M. J. and Spence, M. (1976). Effluent charges and licenses under uncertainty. *Journal of Public Economics*, 5(3-4):193–208.

[131] Rosendahl, K. E. (2019). EU ETS and the waterbed effect. *Nature Climate Change*, 9(10):734–735.

[132] Rubin, J. D. (1996). A model of intertemporal emission trading, banking, and borrowing. *Journal of Environmental Economics and Management*, 31(3):269–286.

[133] Schlenker, W. and Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to us crop yields under climate change. *Proceedings of the National Academy of sciences*, 106(37):15594–15598.

[134] Sheehan, R. G. (1985). Money, anticipated changes, and policy effectiveness. *The American Economic Review*, 75(3):524–529.

[135] Silbye, F. and Sørensen, P. B. (2019). National climate policies and the european emissions trading system. In *Climate Policies in the Nordics. Nordic Economic Policy Review 2019*, pages 63–111. Nordic Council of Ministers.

[136] Sinn, H.-W. (2008). Public policies against global warming: a supply side approach. *International Tax and Public Finance*, 15(4):360–394.

[137] Szabo, M. and Garside, B. (2020). Germany unveils long-awaited coal phaseout bill after cabinet approval. *Carbon Pulse*, 29 January 2020.

[138] Ulph, A. and Ulph, D. (1997). Global warming, irreversibility and learning. *The Economic Journal*, 107(442):636–650.

[139] Van Huyck, J. B., Battalio, R. C., and Beil, R. O. (1990). Tacit coordination games, strategic uncertainty, and coordination failure. *The American Economic Review*, 80(1):234–248.

[140] Weitzman, M. L. (1974). Prices vs. quantities. *Review of Economic Studies*, 41(4):477–491.

[141] Weitzman, M. L. (1978). Optimal rewards for economic regulation. *The American Economic Review*, 68(4):683–691.

[142] Weitzman, M. L. (2019). Prices or quantities can dominate banking and borrowing. *Scandinavian Journal of Economics*.

[143] Wilson, I. G. and Staffell, I. (2018). Rapid fuel switching from coal to natural gas through effective carbon pricing. *Nature Energy*, 3(5):365.

[144] Yates, A. J. and Cronshaw, M. B. (2001). Pollution permit markets with intertemporal trading and asymmetric information. *Journal of Environmental Economics and Management*, 42(1):104–118.

[145] Zhao, J. (2003). Irreversible abatement investment under cost uncertainties: tradable emission permits and emissions charges. *Journal of Public Economics*, 87(12):2765–2789.

CENTER DISSERTATION SERIES

CentER for Economic Research, Tilburg University, the Netherlands

No.	Author	Title	ISBN	Published
617	Matjaz Maletic	Essays on international finance and empirical asset pricing	978 90 5668 618 5	January 2020
618	Zilong Niu	Essays on Asset Pricing and International Finance	978 90 5668 619 2	January 2020
619	Bjorn Lous	On free markets, income inequality, happiness and trust	978 90 5668 620 8	January 2020
620	Clemens Fiedler	Innovation in the Digital Age: Competition, Cooperation, and Standardization	978 90 5668 621 5	October 2020
621	Andreea Popescu	Essays in Asset Pricing and Auctions	978 90 5668 622 2	June 2020
622	Miranda Stienstra	The Determinants and Performance Implications of Alliance Partner Acquisition	978 90 5668 623 9	June 2020
623	Lei Lei	Essays on Labor and Family Economics in China	978 90 5668 624 6	May 2020
624	Farah Arshad	Performance Management Systems in Modern Organizations	978 90 5668 625 3	June 2020
625	Yi Zhang	Topics in Economics of Labor, Health, and Education	978 90 5668 626 0	June 2020
626	Emiel Jerphanion	Essays in Economic and Financial decisions of Households	978 90 5668 627 7	July 2020
627	Richard Heuver	Applications of liquidity risk discovery using financial market infrastructures transaction archives	978 90 5668 628 4	September 2020
628	Mohammad Nasir Nasiri	Essays on the Impact of Different Forms of Collaborative R&D on Innovation and Technological Change	978 90 5668 629 1	August 2020
629	Dorothee Hillrichs	On inequality and international trade	978 90 5668 630 7	September 2020
630	Roland van de Kerkhof	It’s about time: Managing implementation dynamics of condition-based maintenance	978 90 5668 631 4	October 2020

No.	Author	Title	ISBN	Published
631	Constant Pieters	Process Analysis for Marketing Research	978 90 5668 632 1	December 2020
632	Richard Jaimes	Essays in Macroeconomic Theory and Natural Resources	978 90 5668 633 8	November 2020
633	Olivier David Armand Zerbib	Asset pricing and impact investing with pro-environmental preferences	978 90 5668 634 5	November 2020
634	Laura Capera Romero	Essays on Competition, Regulation and Innovation in the Banking Industry	978 90 5668 635 2	December 2020
635	Elisabeth Beusch	Essays on the Self-Employed in the Netherlands and Europe	978 90 5668 636 9	December 2020
636	Sophie Zhou	Innovation and the Macroeconomy	978 90 5668 637 6	November 2020
637	Vincent Peters	Turning modularity upside down: Patient-centered Down syndrome care from a service modularity perspective	978 90 5668 638 3	December 2020
638	Pranav Desai	Essays in Corporate Finance and Innovation	978 90 5668 639 0	January 2021
639	Kristy Jansen	Essays on Institutional Investors, Asset Allocation Decisions, and Asset Prices	978 90 5668 640 6	January 2021
640	Riley Badenbroek	Interior Point Methods and Simulated Annealing for Nonsymmetric Conic Optimization	978 90 5668 641 3	February 2021
641	Stephanie Koornneef	It’s about time: Essays on temporal anchoring devices	978 90 5668 642 0	February 2021
642	Vilma Chila	Knowledge Dynamics in Employee Entrepreneurship: Implications for parents and offspring	978 90 5668 643 7	March 2021
643	Minke Remmerswaal	Essays on Financial Incentives in the Dutch Healthcare System	978 90 5668 644 4	July 2021
644	Tse-Min Wang	Voluntary Contributions to Public Goods: A multi-disciplinary examination of prosocial behavior and its antecedents	978 90 5668 645 1	March 2021

No.	Author	Title	ISBN	Published
645	Manwei Liu	Interdependent individuals: how aggregation, observation, and persuasion affect economic behavior and judgment	978 90 5668 646 8	March 2021
646	Nick Bombaij	Effectiveness of Loyalty Programs	978 90 5668 647 5	April 2021
647	Xiaoyu Wang	Essays in Microeconomics Theory	978 90 5668 648 2	April 2021
648	Thijs Brouwer	Essays on Behavioral Responses to Dishonest and Anti-Social Decision-Making	978 90 5668 649 9	May 2021
649	Yadi Yang	Experiments on hold-up problem and delegation	978 90 5668 650 5	May 2021
650	Tao Han	Imperfect information in firm growth strategy: Three essays on M&A and FDI activities	978 90 5668 651 2	June 2021
651	Johan Bonekamp	Studies on labour supply, spending and saving before and after retirement	978 90 5668 652 9	June 2021
652	Hugo van Buggenum	Banks and Financial Markets in Microfounded Models of Money	978 90 5668 653 6	August 2021
653	Arthur Beddock	Asset Pricing with Heterogeneous Agents and Non-normal Return Distributions	978 90 5668 654 3	September 2021
654	Mirron Adriana Boomsma	On the transition to a sustainable economy: Field experimental evidence on behavioral interventions	978 90 5668 655 0	September 2021
655	Roweno Heijmans	On Environmental Externalities and Global Games	978 90 5668 656 7	August 2021

This dissertation investigates strategies to regulate environmental externalities.

Chapter 1 studies the regulation of stock externalities under asymmetric information and future uncertainty. The chapter derives optimal tax and quota instruments that perform remarkably well, solving the asymmetric information problem almost entirely. This chapter also proves that an optimal tax policy converges to the hypothetical symmetric information outcome two orders or magnitude faster than an optimal quota policy.

In contrast to the focus on novel policies in chapter 1, chapter 2 establishes two unintended yet undesirable side-effects of an existing policy. Due to a 2018 reform, the EU ETS features an endogenous cap on emissions. This chapter shows that, generally, such an endogenous emissions cap may lead to an increase in emissions in response to an anticipated future policy meant to reduce them. Moreover, discontinuities in the design of the EU ETS also introduce equilibrium multiplicity, exposing participating firms to additional uncertainty.

Whereas chapters 1 and 2 study policies by a single policymaker, chapter 3 focuses on collaborations between independent policymakers regulating emissions in their own jurisdictions through a cap and trade scheme. The chapter shows that global welfare always increases after jurisdictions link their schemes and derives an optimal linkage. Though simple, the optimal linkage deviates substantially from existing policy proposals for linking.

The final chapter uses the methodology of global games to study equilibrium selection in a coordination game where players must choose between clean and dirty technologies. The chapter also develops network subsidies. A network subsidy allows the policymaker to correct for the entire externality deriving from technological spillovers but does not, in equilibrium, cost the policymaker anything.

ROWENO JOHANNES RYAN KING HEIJMANS ('s-Hertogenbosch, the Netherlands, 1994) received a B.Sc. and M.Sc. degree in Economics at Tilburg University. In 2017 he started as a Ph.D. candidate at the Department of Economics at Tilburg University under the supervision of prof. dr. Eric van Damme and prof. dr. Reyer Gerlagh.

ISBN: 978 90 5668 656 7
DOI: 10.26116/center-lis-2115

TILBURG SCHOOL OF ECONOMICS
AND MANAGEMENT

CentER Dissertation Series