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Prospects for Markets for Internationally Transferred Mitigation Outcomes under the Paris Agreement

Jon Strand

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Abstract

The Paris Agreement provides for parties to use internationally transferred mitigation outcomes in implementing their Nationally Determined Contributions. This paper analyzes forward trading of these outcomes in the presence of two forms of uncertainty: (1) uncertainty about the fulfillment of Nationally Determined Contribution targets, and (2) uncertainty about the existence and functioning of the forward, options, and future spot markets markets for internationally transferred mitigation outcomes. When parties can sell and buy internationally transferred mitigation outcomes forward, access to call options for late purchases leads to correspondingly larger forward sales, or less current mitigation. Access to put options for late internationally transferred mitigation outcome sales does not affect forward trading outcomes but increases late sales for net sellers. Access to options markets is welfare enhancing for all parties, and call options help parties stay in compliance with their Nationally Determined Contributions at the Paris Agreement end point, 2030. The existence of internationally transferred mitigation outcome markets may be in peril, however, as banking beyond 2030 is not allowed. The availability and functioning of internationally transferred mitigation outcome markets can be enabled or improved by increased climate finance provided by donors. With no options markets, host countries will still sell internationally transferred mitigation outcomes forward, albeit less so, and rely on access to more expensive "backstop" mitigation for ex-post compliance with their Nationally Determined Contributions. Closed-form solutions are derived for trading and its welfare impacts in all the option contract alternatives, given that parties' uncertainties about fulfilling their commitments are uniformly distributed. The welfare impact of the availability of put and call option contracts is then strongly increasing in uncertainty, and in ex-post and forward outcome prices.

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By

Jon Strand

Development Research Group, Sustainability and Infrastructure Team

The World Bank

Jstrand1344@gmail.com

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Prospects for Markets for Internationally Transferred Mitigation Outcomes under the Paris Agreement[1]

1. Introduction and Background

A topical question on today's climate policy agenda is whether markets and infrastructure under the Paris Agreement (PA) will support trading of internationally transferred mitigation outcomes (ITMOs). ITMOs are defined and made precise in relation to Article 6 of the PA. This instrument opens up for participating countries to fulfill their (unconditional) Nationally Determined Contributions (NDCs) toward the PA by trading ITMOs, between selling parties which "over-fulfill" their PA NDCs, and other parties which do not themselves fulfill their NDC targets. ITMOs must be considered in the context of two trading mechanisms under the PA: one mechanism for bilateral trade in mitigation outcomes under Article 6.2; and a new global market mechanism for ITMO trading under Article 6.4. A growing number of parties seem interested in using these mechanisms, although (so far) more parties have expressed interest in selling ITMOs than potentially buying them. Brandemann, Kreibich and Obergassell (2021) found that, by October 2021, 102 of 124 parties analyzed state a willingness to use these market mechanisms in their NDC implementation. See also Michaelowa et al. (2021a). More parties may have become positive after the Article 6 Rulebook was completed at the Glasgow COP-26 in November 2021. Some large parties, notably the United States and the European Union, have however (at this point) expressed a lack of willingness to use these mechanisms.

A final approval and rulebook for the Article 6 mechanisms were produced at the COP 26 in Glasgow, implying that there are now no formal barriers to ITMO trading under these mechanisms; see Michaelowa (2021). Note however that these mechanisms, and ITMO trading, do not themselves lead to reduced targeted emission rates, nor reduced actual emissions given that targets are achieved. Instead, the Article 6 mechanisms imply that costs of reaching the targets are reduced, perhaps dramatically. The markets for selling and buying of ITMOs thus open up for very large potential welfare gains, through reductions in GHG mitigation costs across countries, and corresponding increases in participating countries' mitigation ambitions (by tightening their NDC

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targets), which can result in similar reductions in GHG emissions by 2030 and beyond that date. Edmonds et al. (2021) have estimated that ITMO trading through the Article 6 mechanisms can reduce the costs of achieving the 2030 NDC targets by $300 billion (or about one-third of the total potential ITMO transaction value), which in turn could reduce GHG emissions by an additional 9 billion tons CO_2e per year if reinvested fully in emissions reducing capital and activities. Similar conclusions were drawn in an earlier study by the World Bank (2016). See also the seminal and even earlier study by Metcalf and Weisbach (2012), and more recent work by Mehling, Metcalf and Stavins (2018, 2019), Parry et al. (2021), and Black et al. (2021) for further analysis and discussions.

When selling an ITMO to another party of the PA, the seller must perform a "corresponding adjustment" (CA) exempting the underlying emission reduction from accounting against its own NDC emissions target, to avoid double counting of mitigation outcomes that can be claimed to the parties' NDCs, and attribute the transferred ITMO to the buying party.[2]

A main objective of this paper is to discuss principal and analytical issues related to the functioning of ITMO markets, their impacts on potential ITMO-supplying countries, and their potential for reducing the cost of global GHG mitigation activity, and increase the global ambition in climate policy. Our focus in this discussion will be on impacts of uncertainty, on parties' strategies and activities, and on the functioning of the carbon markets which form the fundaments for these trading mechanisms. A background is a widespread worry that the Article 6 trading mechanisms may not be widely used for PA implementation, due to several factors but with uncertainty as one central issue. The objective of these mechanisms is to facilitate more efficient, effective and broad-based global GHG mitigation for a maximum number of countries. The objective is to make it easier and less expensive for the parties to reach their NDC targets, and to give these countries incentives to set more ambitious NDC targets. As vividly illustrated in Edmonds et al. (2021), when the Article 6 mechanisms are not used (or used only sparingly and inefficiently), overall costs of implementing the required emissions reductions can be (much) higher than necessary, and also make it harder for all countries to reach their NDC targets.

[2] Correct CA accounting requires that strict book-keeping principles are followed by all PA parties; see Schneider et al. (2017).

A reason for this skepticism is a widespread worry among parties about their ability to fulfill their NDC pledges. There is also a worry about whether parties can over-fulfill their NDC targets and do not find countries to which to sell their surpluses. A high degree of uncertainty about a party's mitigation outcome at or close to 2030 could make a participating country highly conservative in its activity to sell ITMOs forward (which must be paired with a CA), given that NDC fulfillment at the end point has high priority for the party. This might severely curtail the supply side of the ITMO market. The anticipation of future supply limitations could in turn have serious knock-on impacts for the demand side. Potential future demanders of ITMOs, who are highly concerned about fulfilling their future NDC requirements, will tend to anticipate the availability of ITMOs required for NDC fulfillment when uncertain variables take their most adverse values, and ITMOs at the same time may not be available for purchase in the ex-post market. When ITMOs are expected to not be available near 2030, these countries may respond by assuring that their NDC requirements will be fulfilled in the absence of late ITMO trading, thus making the ITMO markets redundant. Such behavior among a large number of potential ITMO demanders could thin the market and lead to an unfortunate situation with no or only marginal trading opportunities during the PA implementation period. We might end up with a self-fulfilling belief that such markets will not exist as demand fails due to lack of supply, and supply fails due to lack of demand. Greater uncertainty with respect to future NDC fulfillment could make such problems more likely.

Certain institutional issues related to the PA compound and magnify these worries. The institutional setup of the PA trading system based on Article 6 is problematic, as it does not allow for banking of ITMOs from one NDC period to subsequent ones. This can cause severe problems for the very existence of an ITMO market near the end point. "Nobody" (in particular, no low- or middle-income country) will want to be left with idle ITMOs at the end point (under current rules for the PA, these ITMOs will then be worthless). To guard against this possibility, parties may seek to end trading and achieve ITMO balance relative to their NDCs, in ample time before the end point. This may cause the markets to fail near the end point, which may push back further the time at which a party will decide to stop trading.[3]

[3] It appears that these clauses have been inserted into the PA rulebook to prevent a situation similar to that experienced at the end of the contract period for the KP, which was not suffering from these problems. But under that agreement, some countries were left with substantial amounts of surplus mitigation at the end point which could later be cashed out. Rule makers for the PA wanted to avoid such situations under the current agreement.

A natural question here is whether this problem can be rectified or ameliorated by "soon" altering this institutional setup. Policy makers and other relevant actors need to be alerted about the importance of such rule changes for successful treaty implementation.

There however do exist potentially fruitful responses to problems raised by uncertainty for the functioning of ITMO markets. Which response(s) will turn out as (most) viable depend on several factors, including the participating countries' preferences, their policy options and choices, the costs involved, and institutional details of the PA, to the extent that these can be modified. Assume that a potential ITMO-selling country has already set its NDC target for 2030, and that this country is highly committed to its target. According to the PA rulebook, this target can be tightened but not relaxed. The natural way to respond to greater uncertainty about goal fulfillment is to increase GHG mitigation above its "normal" or "planned" level, to create a "mitigation buffer" that makes target fulfillment more resilient to uncertainty. From that perspective, greater uncertainty can, at least in principle, lead to an increase in mitigation among PA parties, at least given that targets themselves are not moved by such uncertainty.

On the other hand, NDC target setting at later stages of the agreement (e. g., in 2025) may be impacted negatively by uncertainty. NDC targets are expected to be gradually tightened toward 2030. Greater certainty about a party's ability to reach (or over-perform relative to) the current target, and lower costs of reaching this target, may increase the target ambition over time, and greater uncertainty may prevent such greater ambition. Laxer targets could lead to laxer mitigation activity. It is here easy to think of situations where greater uncertainty would reduce global mitigation.

This paper will discuss problems caused by uncertainty for the operation and functioning of ITMO markets: their origins, the forms the problems may take, and possible ways to overcome them. We will be less concerned with impacts on the overall climate policies of PA parties, and how NDC targets are impacted. Our concern will be more about how uncertainty affects the very functioning of ITMO markets.

There are several ways to approach ITMO markets under uncertainty. We will mention three that will play a role in the following discussion.

1. Financial contracts and facilities available to parties, such as option and swap contracts (including also rights of first refusal). The most commonly used contract type to date (for example under the Kyoto Protocol, KP) is simple forward contracts, where ITMOs are contracted between two parties for future delivery at a given contracted price. Put and call options contracts may both also be relevant.[4] Put options for future ITMO sales may serve to guarantee future ITMO market access without imposing on the selling country any obligation to offer the ITMOs, but instead to open up this possibility, and guarantee that the ITMOs need not be sold by hosts which otherwise have problems with fulfilling their NDCs. Such options may be purchased with a contracted "strike price", q_1, at which they will be exercised, and expire 31 December 2030. Call options, for the purchase of ITMOs at future dates (by the PA end point), can be relevant for net ITMO buyers, most likely high- and middle-income countries. They can however also be relevant (in principle) for prospective ITMO sellers, when combined with forward sales contracts for ITMOs at fixed (pre-determined) prices, by serving as a hedge against overselling risk created by the (often lucrative) sale of forward ITMO contracts. Engaging in ITMO forward sales contracts exposes a host to increased risk of NDC noncompliance when emissions turn out to be higher than initially anticipated at or near the end point (2030). ITMOs may in such cases need to be "bought back" for NDC compliance, which could occur safely through call option contracts.[5] Properties of such contracts will be studied in the following, to investigate their roles for the operation of ITMO markets and NDC implementation. No option markets for ITMOs have so far been set up nor seriously contemplated. It is currently unclear whether option contract markets can be made available to PA market participants ahead of 2030; and who would in case sponsor, support, and guarantee their existence and sufficient liquidity. Institutionally, they can be set up as simple bilateral trades between two parties, or as structured markets with sufficient liquidity. We do not take a stand on this in the paper, nor do we study the implications of market structure on their efficiency and attractiveness to the parties. Note that similar market applications to emissions or offset

[4] For standard (textbook) presentations and discussion of options markets and contracts, see Hull (2009) and Shapiro (2006). For classical work on options theory, applied to structured options markets dealing with more general cases than discussed here (and applied mainly to financial asset valuation in continuous time), see Black and Scholes (1973), and Merton (1973).

[5] In a two-country relationship between PA parties, this could occur simply by canceling a forward-contracted delivery of ITMOs at the end point; and thus no "buying back".

trading have been suggested in the literature; see in particular Ismer and Neuhoff (2006), Pizer (2011), Little et al. (2015), Environmental Defense Fund (2016), Coffman and Lockey (2017), and Lockey and Coffman (2018).

2. Other interventions, support and facilitation by donors and/or International Financial Institutions (IFIs), or by other funds and institutions supported mainly by donors. Funds or facilities can be established and created by donors to establish, enable and facilitate the existence and operation of the necessary markets, and access for hosts to these markets, to reduce or eliminate the uncertainties for countries which rely on forward and options markets for ITMOs. Few examples of such support programs exist to date. They typically require resource inputs by donors, but not necessarily very large net donor commitments. Climate finance cannot be used for direct purchase of ITMOs, but may be used to subsidize the ITMO markets (although it is ruled out by some climate finance providers such as the Green Climate Fund (GCF) and the Climate Investment Funds (CIF)). Such subsidies are however in most cases inefficient if they do not serve to correct particular inefficiencies of market operation (see Strand 2019). When support is mainly to the establishment of a viable ITMO market without (substantially) subsidizing its activities, such subsidies can be used, and could also be virtually costless at the margin for funders. Both funders and hosts may instead end up with welfare gains due to the benign impacts on market functioning.
3. Counting on host countries to come up with their own strategies for eliminating possible NDC achievement deficits, either "ex ante" (in a preparatory phase); or "ex post", toward the end of the PA agreement (2030). Host countries could be forced into a situation of responsibility, with a need to eliminate any mitigation deficit relative to their NDC targets, and might end up with innovative ways to reduce their GHG emissions. One (expensive) way to accomplish this is to plan for sufficient over-fulfillment of the host's NDC, to make sure that an end-point mitigation deficit does not arise. The host can, similarly, establish a "buffer" of mitigation activities and projects, that can be activated at a late stage of the PA to guard against unexpected NDC deficits. It might also be done by then activating an "emergency reserve" or "backstop" mitigation activity. These alternatives could however be expensive, and perhaps limited in scope. An advantage of the last alternative for hosts is that it may be needed only with low probability, which means that it would count little

in the host's ex ante calculus. Our analysis below shows that even an expensive backstop alternative could still, in some cases, form the basis for forward ITMO sales.

A problem with such ex-post solutions executed by sovereigns is *lacking ex post incentives*. The incentives to carry out backstop mitigation must be retained at a late stage. But a sovereign host is essentially free to implement or not implement this mitigation "fix". This reveals a fundamental weakness of the PA: it implies no binding commitments on the parties, and is thus unenforceable versus its sovereign member countries. This problem can be reduced to some degree by establishing insurance-like solutions where hosts make payments up front to ensure that default will not occur.

This paper will focus less on other issues which can be crucial for the overall success and impact of the PA: (a) the general GHG mitigation level and policy of the respective host countries, and (b) how countries' NDC targets are defined under the PA. As noted, NDC targets are likely to be set (and further tightened) on the basis of the estimated costs of implementing them. We will assume that NDC targets and GHG mitigation policies are both given, and that comprehensive carbon pricing is the main instrument used by hosts to reach their NDC mitigation targets.[6] We focus on ITMO delivery and NDC target achievement, and impacts of uncertainty on this relationship. Commitment to PA targets is also important. Since the PA relies on voluntary cooperation between all parties, trust in the willingness of the parties to seriously pursue their NDC targets is required. We will (with some qualifications) assume that host countries pursue their NDC targets vigorously. Target definition can also be important. Single- or multi-year target setting can make a difference for target attainment, measurement and recording, and for the integrity of target reaching; see Siemons and Schneider (2021), and Michaelowa et al. (2021b). In our analysis we however make explicit considerations for only one future period.

2. Uncertainty: Sources and Implications

Uncertainties facing PA hosts are key in this paper. Several types of uncertainty face potential ITMO suppliers and demanders, related to costs and efforts needed to reach their NDC targets under the PA; and what measures and market alternatives are available to meet these uncertainties.

[6] Appendix 1 also considers the phasing-in of zero- or low-carbon technologies as the main mitigation strategy, without this altering our results noticeably.

Different uncertainties may interact, be mutually compounded or lessened, and be affected by donors' and other market participants' interventions and policies.

We distinguish between seven categories of uncertainty, of which (at least) five directly impact on hosts' ability to fulfill their NDCs at the PA end point (2030).

a) Lack of knowledge, or uncertainty, by a host country about the shape of its own marginal abatement cost curve ("MAC curve"), and about how the MAC curve will develop up to the PA end point (year 2030). This is a potentially important type of uncertainty for host countries, in terms of predicting their potentials for GHG mitigation by 2030; it plays a key role in our formal analysis. Many country governments, in particular in low-income countries, may have poor knowledge about their own current MAC curves, and an even less secure notion about how these curves will develop over the years to come. This point interacts with and depends on points b-e below. It also depends on the broad category of uncertainty to which this belongs (in particular, Knightian "risk" versus "uncertainty", as discussed below).

b) The fossil fuel price, and other productive input prices, at intermediate stages and end point, are uncertain. A high fossil fuel price gives an automatic impetus to reduce fossil fuel consumption and carbon emissions in both the short and long run. A change in the fossil fuel price should have a similar impact on emissions as an equivalent shift in the carbon tax (at same stage). Note that the international fossil fuel price is likely to be higher when global demand for fossil fuel is higher, which is likely when global GHG mitigation activity is lower, and general economic activity is higher.

c) Whether or not the host country is able to implement a (planned or unplanned) comprehensive mitigation policy (including carbon pricing or wider decarbonization programs) within the policy period; and at what stage and price level carbon pricing is implemented. The host country may have clear plans about how to set its carbon price up to 2030, but both the policy environment and implementation possibilities may be highly uncertain. Significant carbon pricing, and early carbon pricing implementation, lead to lower GHG emissions, and make it more likely that its target will be reached. The host government will however be more certain about this at an intermediate date (such as 2025), at which time the NDC target may be adjusted.

d) Implemented zero- or low-carbon investments up to 2030, and impacts of these investments on mitigation. These are highly uncertain for most PA parties today. The amount of such implementation affects the degree to which the host's emissions level can be shifted down relative to BAU (with no such investments for given policy and activity level); or be shifted up when the BAU is based on (substantial) renewables phase-in. This factor is affected by developments for low-carbon technologies, support received for such implementation, and carbon price implementation (which incentivizes renewable-energy investments).

e) Whether the host' economic activity rate is high or low, and other (random) factors affecting fossil fuel demand. When output is higher more fossil fuels will likely be demanded, and GHG emissions will be higher.

f) The likelihood for (current, future, and forward) ITMO markets to exist; the scope for types of ITMO trading; the liquidity of ITMO markets; and the levels the (current or future expected) ITMO demand including the future ITMO price. A high current ITMO price, combined with readily accessible future or current ITMO markets, should imply strong incentives for GHG mitigation in a host country that expects to deliver ITMOs. A country that instead expects to be a net demander of ITMOs will also prefer a robust ITMO market, but rather one with low ITMO prices. Note that robust and liquid ITMO markets can have either high or low equilibrium prices, depending on the concrete demand and supply conditions.

g) Uncertainty about donor involvement in carbon markets and the availability and use of external funds to stimulate global GHG mitigation and ITMO market activities. Donor support and guarantees may lead to more smoothly operating ITMO markets. When it is unclear whether such support may be forthcoming later in the PA implementation period, it may lead to caution and skepticism among potential hosts who are potential ITMO market participants, and perhaps less reliance on these markets.

Points a-e mainly affect uncertainty about hosts' MAC curves, which will be the main topic of most of our discussion involving uncertainty in the following. Points a, b and e (and in part d) can largely be viewed as "random" factors from the angle of a given host. Points c and d (and in part e) are more related to policy uncertainty. In the following analysis we will mostly assume that uncertainty is purely random and that the host has little or no ability to control it. We will keep most of our attention on point a, when such focus is needed.

Points f-g represent uncertainty related to external conditions facing hosts. They also play a significant role in this paper, as background for much of our concern about non-existence of ITMO markets, and the need for trading alternatives including options markets. As has already been pointed out, ITMO trading holds a great potential for reducing overall costs of implementing parties' NDCs, which could increase parties' mitigation ambitions and overall GHG mitigation by making their NDC targets more ambitious (see Edmonds et al. 2021). On the other hand, if parties' ambitions (and NDC targets) are given, the inability to trade ITMOs could lead to *greater* mitigation under uncertainty. A lack of ITMO market access can induce parties to carry out more mitigation than otherwise in a preparatory phase, to ensure that their NDC targets will be fulfilled later on. But it also increases the parties' interests in more complex contracting, by using options and other forward markets We draw this conclusion in section 4 below.

Other aspects of uncertainty can also be consequential:

1) *Whether uncertainty represents "Knightian risk" or "Knightian uncertainty".* The distinction stems from Frank Knight's (1921) seminal study where risk assumes a known probability distribution, while uncertainty does not. Knightian risk lends itself readily to mathematical modeling, while Knightian uncertainty does not; it does not yet have a firmly established and accepted analytical basis. The two risk concepts can also yield very different (and sometimes unpredictable and surprising) results (see e.g. Nishimura and Hiroyuki 2007). We will in the following take a "risk" approach, but recognize that it may be subject to limitations that will not be further deliberated.
2) *Whether risks are independent or correlated*. We can identify two classes of correlated risk: correlation between the different risks faced by any given host; and correlation between (overall or more specific) risks faced by different countries. We consider both positive and negative correlations. Correlated risks across countries can have negative consequences, even for existence of ITMO markets. The reason is clear: when all countries either "overshoot" or "undershoot" their NDC targets, in either case serious market imbalances can occur, drying up the demand or supply side of the market. Global risk factors, highly correlated across countries, are development of zero-carbon technologies (d), and global business cycles (e). Such uncertainties could lead to strong positive correlations across countries, and to highly unbalanced global ITMO markets. Regarding

risk factors that affect a given country, there can be positive correlation between the phasing-in of zero-carbon technologies (d), carbon taxation (c), and the MAC curve (a). A positive correlation between zero-carbon technology phase-in (d) reducing emissions, and overall activity level (e), would however lead to *opposite* impacts on carbon emissions from these two factors.

3) *Whether and to what degrees risks/uncertainties are recognized by the parties*. We will in the following assume that probabilities experienced by a party (a "host") are mostly subjective as they rely on (Bayesian) beliefs of the parties. They need not be "true" probabilities. For example, a host may have incomplete knowledge about the "objective" probability distribution related to the shape of its own MAC curve, but has a subjective belief about this shape. In our analysis, this host will then act based on its belief, which is not necessarily "objectively correct".

3. ITMO Trading in the Absence of Option Markets

3.1 Initial Setting: Spot Market

We start with a very basic case, setting up our general model structure. We consider a spot market for ITMOs which is active at the end point of the PA (in 2030). The host is assumed to be able to adjust its mitigation activity immediately and optimally to the ITMO price at the end point.[7] The ITMO seller (host country; or project host) is assumed to face either a competitive ITMO market, or unlimited trade with other PA hosts, where an unlimited number of ITMOs can be sold by all private entities in the host economy at a market price q, considered exogenous by the host. We assume that the host has implemented an economy-wide carbon price, t, the only mitigation alternative used. Carbon emissions from the host's energy use is proportional to its fossil-fuel consumption (today, and/or at the time when any future contract can be signed). Call the "business-as-usual" (BAU) carbon emissions R_0; carbon emissions at the end point R_B, and the country's NDC target $R^* < R_0$. R^* and R_0 are both exogenous, and the host only uses fossil-fuel energies in the BAU state. The host is allowed to sell all its emissions reduction beyond its NDC target, $R^* – R_B$, in the ITMO market. We here assume no uncertainty, and no discounting.

[7] This is unrealistic in view of the current rules under which Article 6 operates; in particular, that there is no ITMO market, and no banking of ITMOs, beyond 2030. We may however think of, and here represent, a spot carbon market which could be allowed to evolve over time, also beyond 2030 with a continual sequence of spot market outcomes to which the host in question here adjusts.

The host's net return from its economic activity in 2030 is given by:

$$W_1(q) = R_B - \frac{1}{2}\gamma R_B{}^2 - pR_B - tR_B + q(R^* - R_B) + T\,. \tag{3.1}$$

In equation (3.1), p is the fossil fuel price, and T the government carbon tax revenue (= $t\ R_B$). ITMO sales at the end point are here assumed to be non-negative ($R^* - R_B \geq 0$) for low-income country hosts (on which we focus). Equation (3.1) implies a stylized, linear-quadratic production structure for the ITMO seller, where γ is a scaling constant in the host's macro production function; see Doda and Taschini (2017), Strand (2020a, b), Mundaca and Strand (2021) for recent similar modeling approaches.[8] The private sector's behavior is assumed to be captured by maximizing (3.1) with respect to R_B (taking T as given):

$$\frac{dW_1(q)}{dR_B} = 1 - \gamma R_B - p - q - t = 0 \Leftrightarrow R_B = \frac{1-p-q-t}{\gamma}. \tag{3.2}$$

Assume that the host's baseline emissions rate is given by

$$R_0 = \frac{1-p}{\gamma}. \tag{3.3}$$

This baseline is simply given by a zero ITMO price, and zero carbon tax, in (3.2).

The country's NDC emissions target is defined by

$$R^* = \frac{1-p-s}{\gamma}\,. \tag{3.4}$$

s (> 0) represents the comprehensive carbon price (or tax) required by the host country to (effectively and efficiently) implement its unconditional NDC target R^*. Higher s means that R^* is smaller, and the country's NDC is "more ambitious" (required mitigation to reach the NDC equals $s/\gamma > 0$). s/γ is then simply the additional mitigation beyond BAU required for NDC fulfillment. (s is not an actual carbon tax, but represents the *level of a carbon tax required* to reach the NDC, given no ITMO trading possibilities and no uncertainty.) A more ambitious NDC target

[8] Our production structure represents a simple second-order Taylor approximation to the "true" structure, so that the marginal effects of policy instruments, here the carbon tax t, are constant. This model is a precise representation only for relatively small changes in policy variables.

(lower R^*, and higher s) makes it more demanding for the host to fulfill its NDC, and deliver ITMOs at the final stage. We do not specify what is behind this target.

The host's MAC curve is here linear in t and q; it is represented simply by the first-order condition (3.2). This is an over-simplification, but has the advantage of making the analysis highly transparent, and easy to interpret.[9]

The amount of net forward ITMO contracts sold by the host under certainty is defined as R_I:

$$R_I = \frac{v}{\gamma} = \frac{q+t-s}{\gamma} \quad . \tag{3.5}$$

(3.5) follows from the host's NDC target being accurately met, and is found setting $R_B = R^*$. v can be interpreted as a "net excess carbon price": how much higher must the host's total carbon price, $q + t$, be relative to the carbon price which exactly implements the country's NDC, for the host to be able to sell ITMOs in the amount R_I? When $s > q + t$ (the host has an "ambitious" NDC target), this host is a net ITMO buyer, typical for high-income countries with ambitious NDCs.

3.2 Forward ITMO Contracting When Host NDC Fulfillment Is Uncertain

We will now consider impacts of uncertainty for a host which potentially supplies ITMOs, for the host's mitigation behavior. We represent uncertainty about the host's GHG emissions at the end point in a very simple way, and by a single stochastic variable. We also consider impacts of uncertainty on the host's ability and willingness to engage in forward and options contracting for ITMOs. We introduce two "points of time": "ex ante", when policy is implemented under uncertainty; and "ex post", when the uncertain variable is revealed. For analytical simplicity we assume no discounting between these two time points. We now also assume that the host's GHG mitigations policy must be determined at the ex-ante stage; and that it has no or very small possibilities to adjust its emissions ex post.

We focus on a comprehensive and uniform carbon tax t as the only mitigation policy for the host to reach (or attempt to reach) its NDC target under uncertainty.[10] Define the GHG emissions rate

[9] Note that the MAC curve from (2.2) is linear in the country's policy instrument t.

[10] In Appendix 1 we consider a different alternative where mitigation is implemented by phasing in zero-carbon technology in parts of the economy, and carbon taxation not applied. Our main conclusions are similar in both cases.

of the host country at the end point (2030), R_B, as viewed from the "ex ante" starting point, by the following relation which replaces (3.2):

$$R_B = \frac{1 - p - q - t + z}{\gamma} \tag{3.6}$$

Here z is a random variable (from the point of view of the host) affecting final GHG emissions. Assume that $Ez = 0$, and that z has a uniform distribution on its support $[-z_0, z_0]$. The probability density of z on its support is then constant and equals $1/(2z_0)$. A larger z_0 means greater uncertainty about the host's emissions level at the end point.

The uniform distribution has both advantages and disadvantages relative to other alternatives such as the normal distribution. The uniform distribution is the simplest to handle analytically, and to interpret. Another advantage in our context is that no outcomes can occur outside of a given range. The stochastic variable z has well-defined lower and upper bounds, making it possible for the host to choose a "safe" range for its mitigation which ensures that its NDC will be fulfilled. This is not possible with the normal distribution, where no such bounds exist. A disadvantage of the uniform (rectangular) distribution could be that a bell-shaped distribution often represents a more realistic description of uncertainty in the real world.

Assume that the host cannot guarantee compliance by being able to purchase ITMOs or reduce its own GHG emissions ex post. We first seek to derive the condition under which ITMOs can be sold forward, which is $R_B < R^*$ in the most unfavorable state for the host, namely $z = z_0$. This gives the following condition for positive ITMO delivery by the host:

$$z_1 = q + t - s > z_0 \tag{3.7}$$

Here z_1 is defined as the value of z which makes the host "just" in compliance. Assume $q + t - s > 0$. The condition (3.7) then implies that a positive ITMO supply can be contracted and delivered by the host without compromising its NDC target under certainty (with $Ez = 0$ and $z_0 = 0$); as well as when $z_0 < q + t - s$.

When uncertainty is greater so that $z_0 \geq q + t - s$, ITMOs cannot be contracted forward by the host without the host being in non-compliance in some possible future states. The probability that the host will not be in compliance ex post, when not buying ITMOs back, is $P(0)$ given by

(3.8) $$P(0) = \frac{z_0 - q - t + s}{2z_0}.$$

How the host country will respond to a situation where *P(0)* > 0 depends on additional factors. First, how important is it for the host to *always* "stay in compliance" (be able to honor its NDC)? If this is extremely important, the host may (when feasible) select its own policies and strategies so that this holds in all future states.[11]

Secondly, how difficult is it to use a higher carbon tax, *t*, to increase GHG mitigation at later times? Note that reducing *s* is not allowed under the PA; the NDC target can be tightened over time, but not relaxed.[12]

Thirdly, can the host access an ex-post (late-stage) spot marked for ITMOs where NDC deficits can be eliminated by purchasing offsets? Such a spot market may not become available under current trading rules for Article 6; see section 1.

Fourthly, can or will the host fail to honor a contract for forward ITMO delivery, if necessary to stay in compliance ex post? We do not explicitly model the behavior of parties that issue (and guarantee for) forward ITMO contracts, but (briefly, in the appendix) consider problems caused by breach for parties buying forward ITMO contracts.

4. Alternatives for Improving the Conditions for ITMO Markets and Meeting ITMO Deficits

4.1 Discussion of Alternatives

We will now consider other alternatives for facilitating ITMO trading, combined with meeting potential ITMO deficits by host countries, including those arising from forward ITMO sales, and options contracting. Much of this discussion will deal with how problems for ITMO markets due to risks and uncertainty can be mitigated by the PA parties themselves, and by outside participants such as donors or IFIs. We identify and discuss 9 alternatives:

[11] Such strategies are feasible under our assumption of a uniform distribution of uncertain outcomes for the host. With other distributions, such as normality, this is technically not the case. The host must then always accept some final uncertainty about compliance (with no other ex post remedies).

[12] We can however still think of indirect ways to slacken the NDC target. Assume that a host had anticipated a tightening of its NDC target by 2025. A "real slackening" could mean to not go forward with such tightening.

1) *Planning for NDC over-achievement*. Under uncertainty, the host could simply increase its mitigation action and thereby reduce its expected emissions below its NDC level. In our model, the carbon tax t represents the only explicit mitigation action by the host country. This tax could be raised to a level that makes compliance certain, possibly even with some ITMO forward sales. A necessary condition for this is:

$$t + q \geq z_0 + s . \tag{4.1}$$

$t + q$ can here be interpreted as the host's total carbon price, where we consider q as exogenous for the individual host country. Greater uncertainty means a higher z_0. This increases the carbon tax t necessary to stay in compliance for certain (with no other mitigation or ITMO purchases). With moderate value of s (reasonable for a low-income country with "low" mitigation ambition in its NDC), a limited value of z_0, and a considerable value of q, the value of t fulfilling (4.1) could be small or even negative. Incentives would then be provided for this host to sell ITMOs forward. More generally, greater uncertainty (higher z_0) has a positive impact on mitigation by forcing hosts to "over-shoot" their NDC mitigation target (as the carbon tax fulfilling (4.1) is higher when z_0 is greater).

2) *"Backstop" mitigation*. The host could have available other ("reserve" or "backstop") mitigation alternatives near 2030. In real-world piloting alternatives, a common practice has been to try to identify "reserve" mitigation alternatives that could be less responsive to carbon taxation. "Backstops" may be expensive to execute but may be helpful if the mitigation gap is limited.

3) *Access to (inexpensive) future offset markets*. A host country which fails to be in NDC compliance in 2030 (due to excessive emissions and forward ITMO sales), can then be compliant through ex-post ITMO purchases. With such markets available there should be no fundamental bar to selling ITMOs forward. Existence of a future spot market for ITMOs (with reasonable ITMO price) is however highly uncertain, even unlikely, today. Most hosts will likely be hesitant to enter into forward ITMO sales contracts if they need to rely on this market alternative.

4) *Access to expensive future offset markets*. The quantity of offsets available could be limited in such markets. A cost-benefit analysis may be required to determine whether contracting for future ITMO deliveries is optimal. Also here, there is high uncertainty whether such a market will exist.

5) *Put options for ITMO sellers*. The host may purchase put options to sell ITMOs near 2030, at a given (contracted) ITMO price. The options are executed when the host's GHG emissions rate is below its NDC target. The World Bank has created a Pilot Auction Facility (PAF) for auctioning of options to sell verified climate assets (emissions reductions certificates) at a later date, at an auctioned price where the party offering the lowest sales price wins the auction. The winner is provided a guarantee that the climate asset can be delivered at a future date and price, but has no obligation to sell. See Vivid Economics (2018), World Bank (2017a). In our context, hosts would be given the option to supply ITMOs near 2030 at a fixed price, without obliging the host to sell. Such options purchases can be useful not only for net ITMO sellers, but possibly also for net ITMO buyers. For the latter group, put options could be combined with forward ITMO purchases, which could be excessive and potentially "undone" later by exercising acquired put options. Such transactions however appear as less attractive to low-income countries by imposing early costs (when put options are purchased, and investments made for later GHG abatement), while revenues (from ITMO sales when exercising the put options) come later. Another transaction structure with similar impacts for low-income countries (likely net ITMO suppliers) involves climate finance. An ITMO buyer country can finance mitigation in the low-income country via climate finance, and have the climate finance payment reimbursed when the ITMO transaction takes place ex post (as put options are exercised).

6) *Call options for ITMO sellers*, combining fixed-price forward ITMO sales with state-contingent buyback of ITMOs using call options. This is a somewhat more complex mechanism than put option contracts considered above; no such trades have so far been proposed. Consider a host which has engaged in fixed-price forward ITMO sales but may feel insecure about fulfilling its NDC requirement when uncertainty is unfavorable (z takes high values). This host can then contract a sufficient number of call options, for ITMO purchase near 2030, to stay in NDC compliance and also deliver its ITMOs contracted forward. The relevance of this instrument requires that forward ITMO sales, combined with call options for ITMO buyback, are available to the host at an acceptable ex-post contract price.

7) *Call options for late ITMO purchases by net ITMO buyers*. Forward ITMO contracting is not the only possible forward trading mechanism for net ITMO buyers. Having the option to buy

ITMOs later may be more convenient for hosts whose GHG mitigation cost are particularly uncertain.[13] These hosts are typically high-income countries with ambitious NDC targets.

8) *Use of climate finance and/or donor support*. Climate finance cannot be used for direct purchase of ITMOs, but can be used to support the operation of ITMO markets, when considered as attractive or necessary. The ITMO trading markets, and their use by the parties, may appear (much) less risky when the markets and their transactions are strongly backed by donor financing.

9) *Opening up for Article 6 rules changes*. Several rules today seem relevant for amendment. They include the allowance of banking; the opening up of ex-post markets; and the possibility of opening up to and/or stimulating the formation of carbon clubs under the PA.

We will in the following discuss in more depth, and explicitly analyze, four cases: the options cases 5-7, plus case 2 (ex-post backstop mitigation). These solutions will indicate how they, under our assumptions, can optimally be used by the parties, how trading volumes will depend on relevant parameters, and their welfare impacts, compared to when such alternatives are lacking.

We will also remark that opening up for banking of ITMOs beyond 2030 could have quite different implications given overall over-compliance of parties' NDCs, versus a situation with overall under-compliance. With general over-compliance and perfectly functioning ITMO markets, total ITMOs produced will be excessive and parties will gain from banking their excessive ITMO amounts for use in following trading periods.[14] General, overall, under-compliance will lead to a fundamentally different situation. The ITMO market price in 2030 will then tend to be (very) high, giving parties with surplus ITMOs high incentives to sell these in the market to under-complying parties, instead of banking them. Some or many parties will then not be able to fulfill their NDC commitments, leading to default with possible withdrawal from the PA. Banking will be of little or no value. Intervention of donors in the ITMO market will neither be helpful, except that such interventions can reduce the degree of under-compliance by spurring increased late-stage

[13] A pilot case, where this type of call options are being implemented, relates to an agreement on crediting of GHG emissions reductions from Peru's solid waste sector, between the Peruvian government and the Nordic Partnership Initiative representing Nordic country governments. See Climate Focus (2018).

[14] This has been the situation in the aftermath of the KP: Many parties are still sitting with bankable surpluses that, presumably, can be applied for compliance under the PA.

mitigation (for example, via late scale-up of investments in renewable technologies which are already available).

4.2 Put Options for ITMO Sellers

We first consider put options for ex-post ITMO sales. This is a particularly relevant case for hosts that expect to be net ITMO sellers but may still not sell ITMOs early. We focus on a simple case, where the host is exactly in compliance with its NDC target given no ITMO trade, and has no net forward ITMOs sales, which implies

$$q + t - z_0 - s = 0. \tag{4.2}$$

$q + t$ is the effective carbon price facing the host's private sector. From (4.2), the host is exactly in NDC compliance when its emissions are at a maximum ($z = z_0$), and the host has no net forward ITMO sales nor purchases.

Put options for future conditional ITMO sales cannot by themselves help the host to stay in NDC compliance. But they can increase the host's expected revenues by making ITMO sales available for hosts in ex-post states with low z.

The analytical derivation of the optimal strategy of a host which purchases such options is found in Appendix 2. We there show that the optimal number of put options purchased by the host is

$$v(p) = \frac{z_0 - z_1}{\gamma} = 2\frac{z_0}{\gamma}\left(1 - \frac{q_2}{q_1}\right). \tag{4.3}$$

q_1 is here the price paid per ITMO supplied ex post, and q_2 the cost per put option purchased. From (4.2), when $z < z_0$, the host's ex post emissions are lower, and the host is more in over-compliance versus its NDC, and has more ITMOs to sell ex post. The optimal strategy of the host is to choose a cutoff level for z, called z_1, above which the host covers its entire surplus supply of ITMOs ex post by put options, and below which the number of put options corresponds to the optimal level for $z = z_1$. (4.3) provides the solution for the cutoff level z_1. When z_1 is set higher, the number of put options purchased by the host, $(z_0 - z_1)/\gamma$, is reduced. By reducing the number of put options, the host forsakes the most excessive amounts of possible ITMO sales, related to the lowest realizations of z. Highly excessive ITMO levels occur with a small probability; purchasing extra put options to cover these events is not optimal. z_1 is sensitive to the put option cost, q_2.

Note also that in the extreme case of $q_2 \geq q_1$ (the cost of the option to sell ITMOs is at least as high as the ITMO price), no put options are purchased, since there are no net gains from ITMO sales.

Whenever $q_2 < q_1$, some put options are purchased. Typically, q_2 is only a fraction of q_1, implying that a host's optimal options purchases could be large relative to the maximal number.[15]

Optimized welfare for the host from having access to put options ex post (given no other access to ex-post ITMO sales) is:

$$EW(p) = \frac{z_0}{\gamma}\left(1 - \frac{q_2}{q_1}\right)^2 q_1 + A_1 . \tag{4.4}$$

A_1 is a constant representing welfare without put option access. *EW(p)* implies a non-trivial value of put options access, easily (much) larger than the standard deadweight cost of imposing a moderate carbon tax t (which is $t^2/2\gamma$).[16]

Inefficiency of this solution occurs as the number of ITMOs sold in the most favorable ex post states, with values of z below z_1, is capped by the number of put options purchased, from (4.3).

Arguably, put options for future ITMO delivery will be demanded mainly by higher-income or emerging countries and not by low-income hosts. A cost to cover the option price must be incurred early; the same must any investments required to harness the later mitigation benefits; while the payments for exercising the put options come at the end point. This skew cost-benefit profile might however be alleviated by climate finance payments when such financing is required to make the market operative and available to lower-income hosts.

Finding countries willing to supply such put options may be challenging. They must expect to be future ITMO buyers, thus typically higher-income countries. Expected ITMO buyers also face uncertainty, which may make them unwilling to take ITMOs when these countries happen to be in actual compliance, as ITMOs are not bankable beyond 2030 under current Article 6 rules.

Several questions arise with this analysis, one is whether such an options market will necessarily exist; and if they can be purchased, whether they will always be honored ex post.

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[15] For example, in PAF pilot auctions carried out so far, the transacted put options costs have been between 15% and 40% of the transacted strike price for certified emissions reduction sales.

[16] In particular, note that $2z_0$ represents the range of values of the uncertain variable (with same dimension as t).

Another question is whether an ITMO markets with ITMO market price of at least q_1 will be open near the PA end point. If so, these put options will be worthless. Appendix 2 discusses such cases where put options are honored by the issuer, or are relevant to the host country, with probability $\theta < 1$. We show that the number of put options purchased by the host, $v(p)$, will then equal

(4.5) $$v(p) = 2\frac{z_0}{\gamma}\left(1 - \frac{q_2}{\theta q_1}\right).$$

The number of put options purchased will be reduced. Such purchases become less attractive for the host, as some (good) states will not require put options to be exercised. Welfare for the host will however increase due to the occurrence of the future good states.

4.3 Call Options for Net ITMO Sellers

In this alternative, the host sells ITMOs forward early, and guards against future NDC non-compliance by purchasing ITMOs near 2030, by exercising call options.

The host's NDC target is still given by (3.4), and its emissions in 2030 given by (3.6).

A detailed analysis of this case is found in Appendix 3. A main result is that the host will sell an amount of ITMOs forward equal to v/γ, given by

(4.6) $$\frac{v}{\gamma} = \frac{q + t - z_0 - s}{\gamma} + \frac{2(q - q_4)z_0}{\gamma q_3} .$$

Here q_4 is the call option price, while q_3 is the cost of ITMO buybacks in 2030. We assume that $q_3 > q$ (the contracted price of ex-post ITMO buybacks is higher than the ITMO forward price). The number of call options purchased by the host is:

(4.7) $$\frac{v(c)}{\gamma} = \frac{2(q - q_4)z_0}{\gamma q_3} .$$

Regardless of the cost of ITMO buybacks, the host will choose to purchase at least some call options for such buybacks. The reason is that when only a few ITMOs are sold (and a few call options purchased), the probability that the host will need to purchase ITMOs ex post to stay in compliance is very small; while the forward sale of the corresponding ITMOs occurs for certain. The host must here be assumed to have the incentives to incur the buyback cost q_3 ex post.

When (4.2) holds (the host is exactly in NDC compliance in its worst state given no call option access), the first main term in (4.6) drops, and the number of ITMOs sold forward equals the number of call options purchased. This number depends on the ITMO forward sales price, q, minus the call option price q_4, incurred for all ITMOs sold, as all ITMOs may (in the worst case) need to be bought back for the host to stay in compliance for certain. The volume of ITMOs sold forward is reduced proportionately by the cost per ITMO purchased ex post, q_3; and increased proportionately by z_0 which indicates the uncertainty facing the host ex post.

Under certainty about the host's emissions ($z_0 = 0$), the host buys no call options, and sells no ITMOs forward. Any forward ITMO sales would need to be matched by ITMOs purchased ex post for certain, which is here more expensive.[17] All ITMOs must be purchased back, at a higher cost q_3 per ITMO, and q_4 must be paid for availability of each option.

Given that (4.2) holds, the host's GHG emissions are (using (3.6))

(4.8) $$R_1 = \frac{1-p-s-(z_0-z)}{\gamma}$$

Emissions are lower than the NDC target given by (3.4). The host country is still in non-compliance for values of z close to (not much below) z_0, due to the host's forward sale of ITMOs from (3.4). The host is exactly in compliance, purchasing no ITMOs back, when $z = z_1$.

Optimized net welfare for the host from access to call options is found as:

(4.9) $$EW(opt) = \frac{(q-q_4)^2 z_0}{\gamma q_3} + A_2 ,$$

where A_2 is a constant.

This sub-section has not discussed features of the supply side of this type of options contracting. Reasonably, such call options will typically be offered and issued by net ITMO sellers. A question is then whether the option issuer will honor its contractual duty to supply the required ITMOs if the call options are exercised by the option buyer in 2030. This is not problematic with more developed contingent or spot ITMO markets available at a late stage of the PA. Note however that

[17] It can here not be advantageous for the host to sell additional ITMOs forward, and buy them back later under certainty.

it is exactly the possibility of not having such markets available, that raises the need for option contracting in the first place. A further question arising is then whether it may be necessary to provide availability of such options for hosts, using climate finance or other donor or IFI support.

On the other hand, if spot markets for ITMOs with low ITMO prices are available in 2030, the purchased call options will turn out to be unnecessary and not exercised.

Appendix 3 discusses both these cases. It is shown that uncertainty about the ability to exercise call options leads to a lower demand for such options. When ex-post ITMO spot markets with low ITMO prices are available, the number of call options purchased *increases*. This is because forward contracted ITMO sales then becomes more attractive for hosts. Each forward sale needs to be covered by one call option for the host to still guarantee to stay in compliance in all possible states.

Consider finally how q_3 (the contractual ITMO buyback price) and q_4 (the call option price) are set. The call option issuer can keep its value of offering the call option contract at a given level by reducing q_3 and increasing q_4. It should then be possible for the seller to push the ex-post price, q_3, down to a manageable level by increasing q_4. q_3 can then be set to ensure that the option will actually be exercised when needed. We assume as noted that $q_3 \geq q$, but may still be limited so that the ex-post incentives to buy back ITMOs are preserved.[18]

4.4 Call Options for ITMO Buyers

We will now consider the use of call options for contingent future ITMO purchases by parties which expect to be net ITMO buyers. These parties will more typically be high-income (or emerging) but not low-income countries. We will assume that these parties have access to a call options market; call option contracts are honored ex post; and hosts do not have access to an ex-post spot market for ITMOs. We still focus on a case where the party (net ITMO buyer) is exactly in compliance (but not in over-compliance) in its ex-ante state with highest GHG emissions (when $z = z_0$). Assume that these parties can sell and buy ITMOs in the forward market, but have zero net purchases of ITMOs. These countries are assumed to have "ambitious" NDC targets, implying that

[18] This is different from the case, studied in sub-section 4.5 below, where an expensive "backstop" technology needs to be used for NDC compliance, which may not be ex-post incentive compatible for the host.

s in (3.4) is "high". Such countries have incentives to use call options so as to reduce their carbon tax, t, required for NDC compliance.[19]

(4.10) $$ER_2 = \frac{1-p-t-q}{\gamma} = \frac{1-p-s-z_0+v}{\gamma}.$$

In this case, $t = s + z_0 - q - v$, which means that when the number of call options, v/γ, is increased, the party's carbon tax can be reduced equivalently. This reduces the party's deadweight loss related to the carbon tax. The total carbon price for this host is in this case still $t + q$. The party's GHG mitigation is implemented by reducing its carbon tax to t-v, where v/γ is the number of call options acquired by the party for later possible ITMO purchases.

The party's optimal call option purchase level is (see Appendix 4):

(4.11) $$\frac{v(c)}{\gamma} = \frac{2(z_0+s-q_4)z_0}{\gamma(2z_0+q_3)}.$$

(4.11) resembles (4.7) in sub-section 3.3, but differs somewhat. Call options are here purchased for two reasons: because it allows the party to relax its carbon tax, which is beneficial (as the party's economic deadweight loss is reduced); and for holding call options which is an efficient way for the host to meet possible NDC under-compliance under uncertainty, when an ITMO spot market near the end point (with low ITMO prices) may not exist.

With certainty about the host's emissions ($z_0 = 0$), from (4.11) no call options are purchased. The country then uses only the carbon tax, t, to stay in NDC compliance. Under uncertainty ($z_0 > 0$), the country always purchases some call options regardless of their costs, represented by the two cost variables, q_3 (the contracted cost of acquiring ITMOs at a late stage), and q_4 (the cost per option).[20] Th number of call options purchased increases with the level of uncertainty (z_0), and when q_3 and q_4 are lower. Greater uncertainty leads to a need for more forceful mechanisms to avoid being in non-compliance. $v(c)/\gamma$ drops when either cost element, q_3 (the contracted ITMO

[19] A simplification in this case is to assume that these parties do not purchase ITMOs forward to reduce their statutory carbon tax by even more than what is accomplished by (4.10). The carbon tax is reduced only to the extent that call options for future ITMO purchases are acquired. See Appendix 4 for further discussion of this case.
[20] A condition is here $z_0 + s - q_4 > 0$, which we assume holds.

price) or q_4 (the cost per call option) increases. $v(c)/\gamma$ can be higher or lower in (4.11) compared to (4.7). It is lower (higher) when the ITMO forward trading price, q_3, is high (low).

Also here, as in sub-section 4.3, we assume that no ex-post spot market for ITMOs with "moderate" ITMO prices (lower than q_3) is available during late stages of the PA (near 2030). With a positive ex-ante probability that such markets are available, it becomes more attractive to utilize late-stage alternatives for ITMO purchases, since purchasing offsets through the late ITMO market is then cheaper. This also stimulates the net ITMO forward sale, which must be matched with acquiring more call options (to ensure NDC compliance when the ITMO spot market is not available). The solution is further discussed in Appendix 4.

4.5 Forward Contracting of ITMO Sales with Unlimited (Expensive) Backstop Mitigation

We now consider a case where option contracts are not available, the host can sell ITMOs forward, and a "backstop" exists which enables the host to supply extra mitigation at a cost r per ton of CO_2 abated ex post. We assume that the cost r is "high" relative to the forward ITMO price, q.

There are (at least) three approaches to this problem. With the first, the host has no limits on ex post mitigation at unit cost r.[21] The second approach implies a limit, R_0, on ex post mitigation at this cost. Both these approaches assume that the host country is willing to implement this expensive mitigation ex post. A third alternative is that the host's lacks the willingness to comply with its NDC commitment ex post when r is above a certain level.

a) No constraints on backstop mitigation

We first assume no constraints on the host's ability and willingness to implement extra mitigation ex post, at constant marginal cost r. This cost must be compared to the benefit of the ITMO sales at price q, in amount v/γ. When the host is exactly in NDC compliance in the worst possible state when not selling nor buying ITMOs forward ($q + t - z_0 - s = 0$; (4.2) holds), optimal forward ITMO sale equals ex-post backstop mitigation, $v(b)/\gamma$ (see Appendix 5):

(4.12) $$\frac{v(b)}{\gamma} = 2\frac{qz_0}{\gamma r}.$$

[21] More reasonably in this case, the marginal cost of additional mitigation would not be constant but instead increasing. This can be treated relatively simply by assuming that the relevant marginal cost, r, is what will be realized at the equilibrium point.

(4.12) takes virtually the same form as (4.7) for purchase of call options to stay in compliance ex post. A difference is that (4.12) has no deduction for purchase of call options (represented by q_4 in (4.7)), but on the other hand a (much) higher cost of ex post mitigation, r, relative to the ex-post ITMO price, q_3, in (4.7).

r could be large relative to q. For example, if $r = 2q$, the number of ITMOs sold forward is $v/\gamma = z_0/\gamma$. In this special case, ITMO forward sales comprise half the difference in emissions across the entire ex post emissions distribution facing the host. Whenever the mitigation distribution has a positive spread ($z_0 > 0$), ITMO forward sales will be positive regardless of the backstop cost (any large r leaves $v/\gamma > 0$). Higher r reduces forward ITMO sales proportionately.[22] As in cases with options, ITMO sales also increase with greater uncertainty (higher z_0). Greater uncertainty provides more scope for gains by selling ITMOs forward, and cover deficits ex post with backstop mitigation. Put otherwise, while ITMO forward sales have probability one, the ex-post backstop mitigation costs have lower probability and have less weight in the calculous of the host.

Optimized net welfare of having access to the backstop alternative is (see Appendix 5)

(4.13) $$EW_{ES}* = \frac{q^2 z_0}{\gamma r} + A_4,$$

Where A_4 is a constant. The host's GHG emissions rate is here determined in the same way as in Appendix 3.

Our assumption of a constant marginal cost of additional backstop mitigation, r, is unrealistic. More likely, r increases in the amount of backstop mitigation applied. If so, formulas (4.12) and (4.13) are imprecise, as r would need to be replaced by the marginal mitigation cost at the equilibrium point, r'. Typically, $r' > r$; $v(b)$ would be reduced, and $R_{ES}*$ could be higher or lower.

b) Constraints on amount of backstop available ex post

Consider a limit R_0 on the amount of ex post mitigation available to the host. This translates to a maximum ex ante ITMO sale given by $v_0/\gamma = R_0$. This constraint will have an impact if and only if $R_0 < v/\gamma$ from (4.12). The host country's ITMO forward sales will then equal R_0.

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[22] In our model r is assumed constant. It is much more realistic for r to increase in the amount of backstop mitigation. r should then be replaced by its marginal value in (4.12), which provides an approximation.

c) Lack of willingness to stay in NDC compliance ex post

When r is (very) high, backstop mitigation may not be executed even when available. Consider z close to z_0 ex post, so that the host would be NDC non-compliant in the absence of backstop mitigation given forward ITMO sales, and has no other mechanism for achieving compliance, and no further ex-ante arrangements to ensure compliance. Assume that the available amount of backstop mitigation exceeds $v(b)/\gamma$ from (4.12). It is then *ex ante* optimal for the host to resort to backstop mitigation to stay in compliance. But *this may not be optimal ex post*. When the host is not able to commit to later mitigation ex ante, it may not be willing to execute it ex post. When z turns out to be close to z_0, the host country may instead choose to default on its NDC commitment if that is viewed as a "cheaper" alternative, including reputational or other losses following from an NDC default.

This outcome may have several backgrounds. The host country may have a different government in 2030 which may not wish to carry out the required (perhaps, painful) ex post mitigation imposed by another government. Similar cases were observed under the Kyoto Protocol (KP), even for wealthy countries. Canada opted out of the KP when it discovered, near the end of the implementation period, that compliance was not achievable with current mitigation instruments. Australia dropped out when changing to a more conservative government.

When the host country's primary target is to stay in NDC compliance ex post, and does not have access to offset markets ex ante nor ex post, greater uncertainty about the emissions level at the end point will tend to increase its early GHG mitigation activity. In one sense this is "helpful" as it serves to increase a country's overall mitigation level. On the other hand, it increases the host's mitigation costs; and makes it less attractive to the host to later tighten its NDC target. It also provides for an inefficient solution as the countries with the greatest relative uncertainty are those most in need to overshoot their mitigation levels.

We finally remark that a very similar "backstop" alternative can be developed also for net ITMO buyers, in similar fashion to the analysis in sub-section 4.4. Instead of using the backstop alternative to expand its forward sales of ITMOs, such a host will rather reduce its GHG mitigation, by lowering its carbon tax t, as a more economical alternative for such a host.

4.6 Use of Climate Finance and Other Donor Support

In the alternatives we have discussed it is far from clear that the required markets can be enabled. The option market solutions require a credible and liquid option supply side to satisfy option demand; and these markets must be sufficiently liquid to always satisfy desired supply. Existence of such markets in 2030 cannot be guaranteed under current Article 6 rules. A key problem is that banking of ITMOs beyond 2030 is not allowed under current rules. Trading of put or call options at or near the end point could be problematic when the issuing party is in over-compliance and at the same time is required to purchase ITMOs when put options are executed; or is in under-compliance when required to sell ITMOs when call options are executed. Positive correlations of mitigation across hosts can exacerbate these problems.

A question is whether donor funding can overcome such problems. Note then first that climate finance is not allowed for direct purchase of ITMOs. Subsidizing ITMOs through providing climate finance to underlying mitigation activities is not prohibited by Article 6 rules but typically inefficient (Strand 2019). But when the alternative is possible lack of market existence, external finance which enables these markets could have substantial positive efficiency impacts.

There exist technical ways in which donor funding can be deployed for ITMO market support in these situations. One donor (or donor group) could set up two technically separate modes of ITMO market and ITMO financing: one climate finance fund, and one "ITMO fund".

This donor could then support mitigation activities in low-income countries with its climate finance, and at the same time purchase "conditional call options" for ITMOs corresponding to the emission reductions achieved with the supported mitigation activity. The host would then be obliged to transfer ITMOs only if it achieves over-compliance relative to its NDC target (and the ITMO transfer would be ex-post to target achievement).

If the call option alternative is exercised by the host, the donor would need to use its ITMO funding to repay its ex-ante provided climate finance.

More generally, all providers of climate finance could consider allowing for similar ITMO transfers, provided that the climate finance is being reimbursed by ITMO funds.

A question is whether donors would be willing to put up funds for such purposes, in adequate amounts to assure market actors that ITMO markets will be operative during the final stages of the PA. As of today, resources allocated globally to dedicated climate finance are small (of the order \$3 billion per year) and could currently not play such a role.[23] On the other hand, presuming that donors have serious concerns for mitigation at a global level, one could easily envisage a big increase in such funding if necessary to make the ITMO markets operative and credible, when this is fully recognized by donors and effectively communicated to the relevant PA parties. Excess funds would then be used for purchasing and stimulating global mitigation in excess of NDC targets (also beyond the targets of these donors). The key issue for donors should then be the cost imposed on them per ton CO_2 mitigated, which could be moderate, or even potentially negative if ITMO market efficiency (or even market existence) would otherwise be in peril.

4.7 Opening Up for Article 6 Rule Changes

A main Article 6 rule change, that could improve on the possibilities of market existence and functioning, would be to allow for banking of ITMOs beyond 2030, and to the next implementation period of the PA. Revisions of Article 6 rules are however not planned to happen until 2028, which would be too late to have impact for the current implementation period which ends in 2030. Thus, unfortunately, the possibility for such rules changes to have impacts on execution of the PA agreement at the moment (May 2022) seems remote.

5. Conclusions and Final Comments

We have in this paper discussed issues raised by uncertainty about NDC compliance among parties to the Paris Agreement (PA), and how these problems can be alleviated by alternative market modes of ITMO transactions. The traditional market form, used widely for the two trading mechanisms, the Clean Development Mechanism (CDM) and Joint Implementation (JI), under the KP, was (early-stage) forward contracting with later verified emissions reduction (VER) delivery (corresponding here to ITMO delivery). With high uncertainty about mitigation outcomes (and parties' abilities to fulfill their NDC responsibilities based on own policies only), such forward contracting may under the PA however jeopardize NDC fulfillment. Parties may then need to have available additional strategies and market mechanisms to ensure NDC compliance. This paper

[23] See World Bank 2020.

emphasizes four alternatives for handling such uncertainties. Three of them imply using option markets: 1) Put option contracts for ITMO sellers, for late ITMO sales when sellers are in NDC over-compliance. These are relevant for parties which aim to be net sellers in the ITMO market and do not (necessarily) expect a future spot market for ITMOs with high ITMO prices. 2) Forward ITMO contracting combined with call options for (late) buyback of ITMOs, for ITMO sellers. 3) Call options for late ITMO buybacks to be used by ITMO net buyers. Alternatives 2 and 3 are relevant for the parties when future ITMO spot markets with "reasonable" (low) ITMO prices cannot necessarily be expected. The fourth alternative relies on establishing precautionary strategies for mobilizing extra ("backstop") mitigation options. The paper provides explicit and highly intuitive solutions for optimal option purchases and precautionary strategies, which rely on specific assumptions about production structure (linear-quadratic production functions) and uncertainty regarding hosts' ex post GHG emissions (uniform probability distributions).

Among the four alternatives analyzed, 1 and 2 both serve to reduce or eliminate the risk of non-compliance under uncertainty for ITMO sellers; while at the same time making sure that these hosts can engage in forward ITMO transactions when desirable. Alternative 2 embeds a more advantageous revenue profile for low-income hosts than alternative 1, as alternative 2 permits hosts to sell ITMOs forward at a possibly high value, thus obtaining net mitigation-related funds early. Alternative 1 instead implies early costs (for purchasing put options), while revenues (from ITMO sales) come later. Alternative 3 is most relevant for higher-income countries which are uncertain and worried about their final NDC compliance.

We have also calculated the welfare gains for a party from having access to each of the four alternatives, under our model assumptions. These welfare gains can be substantial. One might here think of a net welfare gain relative to the "backstop" alternative which does not depend on options markets. Note that we have not considered welfare gains for "the other party" to each type of options market transaction (e. g., the ITMO buyer in cases where ITMO seller welfare change in calculated), which may also be substantial.

For all the three options alternatives we have studied, market non-existence and failure are clear possibilities as "the other side" of the market may in all cases be thin or even absent. Market support by donor or IFI funding may be required for assuring that these markets function adequately. We have argued that donors may be willing to (and ought to) put up the required funds to ensure smooth ITMO and options market functioning. Our “backstop” alternative can be considered a “reserve” (or “last resort”) alternative relevant only when no other alternatives are available for relevant hosts. We show that even when expensive “last resort” mitigation may in some cases be necessary for a host to stay in ex-post compliance, (potential) ITMO-selling hosts may still be willing to sell ITMOs forward and use the “backstop” alternative for ex-post compliance at least to some degree. But high cost of the “backstop” can be problematic as ex-post incentives to implement it may fail; if so, this alternative will no longer be incentive compatible and thus not viable.

We have throughout assumed that all parties are highly committed to fulfilling their NDCs, and that uncertainty for individual hosts takes a very simple form and is limited to a given range of outcomes, determined by a uniform distribution. We assume that all hosts make sure, through sufficient levels of GHG mitigation, that their NDC targets will be reached for certain. In our analysis we have also, for the most part, taken each party’s basic GHG mitigation level, as well as its NDC target setting, as exogenous. A complete analysis of these topics is beyond the range of what this paper can cover.

A main result from our analysis is that uncertainty about mitigation outcomes makes hosts more cautious in their mitigation policies, which means more mitigation and lower emissions than otherwise. In this sense, uncertainty can be considered as helpful to global mitigation. But such an unambiguous conclusion might ignore important dynamics related to PA implementation. NDC mitigation targets are flexible, and are expected to be updated and made more ambitious as the PA implementation period progresses. As we have shown, the parties’ welfare is increased substantially by access to forward and option markets. Getting access to these markets can then give “room for” selecting higher NDC ambition levels and more ambitious mitigation targets. Edmonds et al. (2021) indicates that use of the Article 6 trading mechanisms could lead to a drastic increase in mitigation implemented by the PA, and is based on exactly this argument. A key point here is that the process of updating to more ambitious NDCs over time can be curtailed when uncertainty is greater. The overall impact of uncertainty on global GHG mitigation under the PA is then unclear.

This paper represents the first formal analysis of the implications of options market trading for the operation and likely outcomes for global GHG mitigation under the PA. Several loose ends are however left. We have focused on the demand side of the forward ITMO markets and not, in similar formal ways, analyzed these markets' supply sides. We have neither discussed, to any depth, all relevant issues related to the overall functioning of the ITMO markets. We need to further study key differences that are likely to arise with general over-compliance (when parties typically wish to bank excessive ITMOs), versus general under-compliance (when defaults will occur, with some, perhaps many, parties withdrawing from the PA). Another weakness is that only two points of time, "ex ante" and "ex post", are explicitly considered in the analytical modeling. Instead, several intermediate time points could be relevant at which stock taking and NDC updating will take place. The paper specifies no mechanism for possible updating of NDCs, nor for updating of uncertain variables and states and the optimal climate policy responses to these. Such topics must be left for future research, hopefully soon as the need for well-functioning markets for implementing the PA targets, and a full understanding of how such markets work, is already urgent, and will soon become even more urgent.

References

Black, F. and M. Scholes. 1973. The Pricing of Options and Corporate Liabilities. *Journal of Political Economy*, 81, 637-659.

Black, S., I. Parry, J. Roaf and K. Zhunussova. 2021. Not Yet on Track to Net Zero. The Urgent Need for Greater Ambition and Policy Action to Achieve Paris Temperature Goals. IMF Staff Climate Note 2021/005. Washington D.C.: International Monetary Fund.

Brandemann, V., N. Kreibich and W. Obergassel. 2021. Implementing Paris Cooperatively. Update on Market Mechanisms in the Latest NDC Submission. Working paper, Wuppertal Institute.

Climate Focus. 2018. Opportunities for the Implementation of Article 6 of the Paris Agreement in the Solid Waste Sector in Peru. Report for the World Bank.

Coffman, D. A. and Lockley. 2017. Carbon Dioxide Removal and the Futures Market. *Environmental Research Letters*, 12, 015003.

Doda, B. and L Taschini. 2017. Carbon Dating: When is it Beneficial to Link ETSs? *Journal of the Association of Environmental and Resource Economists*, 4, 701-730.

Edmonds, J., S. Yu, H. McJeon, D. Forrister, J. Aldy, N. Hultman, R. Cui, S. Waldhoff, L. Clarke, S. de Clara and C. Munnings. 2021. How Much Could Article 6 Enhance Nationally Determined Contribution Ambition Toward Paris Agreement Goals Through Economic Efficiency? *Climate Change Economics*, 12, No. 2, 2150007. https://www.worldscientific.com/doi/epdf/ 10.1142/S201000782150007X.

Environmental Defense Fund. 2016. Options Market and Risk-Reduction Tools for REDD+. Report to NORAD.

Golub, A. et al. 2018. Escaping the Climate Policy Uncertainty Trap: Options Contracts for REDD+. *Climate Policy*, 18, 1227-1234.

Hession, M. 2021. Taking the Long-term Perspective: Baseline Methodologies and Responding to the Challenges of Paris. *Carbon Mechanism Review*, 9, 90-95.

Hull, J. C. 2009. *Options, Futures, and Other Derivatives*. 7th Edition. Upper Saddle River, N. J.: Pearson Prentice Hall.

IISD. 2016. Supporting Energy Pricing Reform and Carbon Pricing Policies Through Crediting. Winnipeg, Manitoba, Canada: International Institute for Sustainable Development.

Ismer, R. and K. Neuhoff. 2006. Commitments Through Financial Options: A Way to Facilitate Compliance with Climate Change Obligations. Working Paper 0625. Cambridge: Electricity Policy Research Group.

Koakutsu, K. and K. Takahashi. 2021. Ensuring Ambitious Baselines. Baseline approaches under Article 6.4. *Carbon Mechanism Review*, 9, 84-90.

Knight, F. H. 1921. *Risk, Uncertainty, and Profit*. Boston: Hart, Schaffner & Marx.

Little, L. R., A. J. Hobday, J. Parslow, R. C. Davies and R. Q. Grafton. 2015. Funding climate adaptation strategies with climate derivatives. *Climate Risk Management*, 8, 9–15.

Lockley, A. and D. M. Coffman. 2018. Carbon Dioxide Removal and Tradeable Put Options at Scale. *Environmental Research Letters*, 13, 054034.

Mehling, M. A., G. Metcalf and R. N. Stavins. 2018. Linking Climate Policies to Advance Global Mitigation. *Science*, 359, 997-998.

Mehling, M. A., G. Metcalf and R. N. Stavins. 2019. Linking Heterogeneous Climate Policies (Consistent with the Paris Agreement). *Environmental Law*, 48, 647–690.

Metcalf, G. E. and D. Weisbach. 2012. Linking Policies when Tastes Differ: Global Climate Policy in a Heterogeneous World. *Review of Environmental Economics and Policy*, 6, 110–129.

Merton, R. C. 1973. Theory of Rational Option Pricing. *Bell Journal of Economics and Management*, 4, 141-183.

Michaelowa, A. 2021. COP-26 Follow-Up. Presentation, Climate Perspectives Group, November 15, 2021.

Michaelowa, A., D. Brescia, N. Wohlgemuth, H. Galt, A. Espelage and L. Moreno. 2020. CDM Method Transformation: Updating and Transforming CDM Methods for Use in an Article 6 Context. Study commissioned by the Swedish Energy Agency.

Michaelowa, A., A. Espelage, L. 't Gilde, N. Krämer, P. Censkowsky, S. Greiner, H.-M. Ahonen, G. A. Victoria, S. Hoch, S. Ombuya, S. Dalfiume. 2021(a). Article 6 Readiness in Updated and Second NDCs. Freiburg: Perspectives Working Paper.

Michaelowa A., L. Hermwille, A. Espelage and K. Michaelowa. 2021(b). Ambition Coefficients: Aligning Baselines for International Carbon Markets with Net Zero Pathways. *Carbon Mechanism Review*, 96-101.

Montero, J. P. 2000. Optimal Design of a Phase-in Emissions Trading Program. *Journal of Public Economics*, 75, 273-292.

Mundaca, B. G. and J. Strand. 2021. Unconditional and Conditional NDCs Under the Paris Agreement: Interpretations and Their Relations to Policy Instruments. Unpublished.

Nishimura, K. G. and O. Hiroyuki 2007. Irreversible Investment and Knightian Uncertainty. *Journal of Economic Theory*, 136, 668-694.

Nordhaus, W. 2019. Climate Change: The Ultimate Challenge for Economics. *American Economic Review*, 109, 1991–2014.

Oi, W. Y. 1961. The Desirability of Price Instability under Perfect Competition. *Econometrica,* 29, 58-64.

Parry, I., V. Mylonas and N. Vernon. 2021. Mitigation Policies for the Paris Agreement: An Assessment for G20 Countries. *Journal of the Association of Environmental and Resource Economists*, 8, 797-823.

Pizer, B. 2011. Seeding the Market. Auctioned Put Options for Certified Emission Reductions. Policy Brief 11-06, Nicholas Institute, Duke University.

Schneider, L., J. Füssler, A. Kohli, J. Graichen, S. Healy, M. Cames, D. Broekhoff, M. Lazarus, S. La Hoz Theuer and V. Cook. 2017. Robust Accounting of International Transfers under Article 6 of the Paris Agreement. Discussion Paper, German Emissions Trading Authority, Berlin.

Shapiro, A. C. 2006. *Multinational Financial Management*. 8th Edition. New York: John Wiley & Sons.

Siemons, A. and L. Schneider. 2021. Averaging or Multi-year Accounting? Environmental Integrity Implications for Using International Carbon Markets in the Context of Single-year Targets. *Climate Policy*, 14693062.2021.2013154.

Steckel, J. C., S. Renner and L. Missbach. 2021. Distributional Impacts of Carbon Pricing in Low- and Middle-Income Countries. *CESifo Forum* 5/2021, Volume 22, September 2021.

Stiglitz, J. E., N. Stern et al. 2017. Report of the High-level Commission on Carbon Pricing. Washington D. C.: the World Bank.

Strand, J. 2019. Climate Finance, Carbon Market Mechanisms and Finance "Blending" as Instruments to Support NDC Achievement under the Paris Agreement. Policy Research Working Paper, WPS8912, the World Bank.

Strand, J. 2020(a). Transformational Climate Finance: Donors' Willingness to Support Deep and Transformational Greenhouse Gas Emissions Reductions in Lower-Income Countries. Policy Research Working Paper, WPS9251, the World Bank.

Strand, J. 2020(b). Supporting Carbon Tax Implementation in Developing Countries through Results-Based Payments for Emissions Reductions. Policy Research Working Paper, WPS9443, the World Bank.

Transformative Carbon Asset Facility. 2022. Different Approaches to Mitigate Overselling Risks of Mitigation Outcomes under Article 6 of the Paris Agreement. Unpublished, World Bank.

Vivid Economics. 2018. The Potential for Climate Auctions as a Mechanism for NDC Implementation. Report to the World Bank.

World Bank, Ecofys and Vivid Economics. 2016. *State and Trends of Carbon Pricing 2016*. Washington DC: the World Bank.

World Bank. 2017(a). Pilot Auction Facility for Methane and Climate Change Mitigation. In: New York Climate Week Roundtable. New York: World Bank Group.

World Bank. 2017(b). Results-based Climate Finance in Practice: Delivering Climate Finance for Low-carbon Development. Washington D.C.: the World Bank.

World Bank. 2020. Transformative Climate Finance: A New Approach for Climate Finance to Achieve Low-Carbon Resilient Development in Developing Countries. Washington, D.C.: the World Bank.

World Bank. 2021. *State and Trends of Carbon Pricing 2021*. Washington D.C.: the World Bank.

Appendix 1: GHG Mitigation via Investments in Non-Carbon Infrastructure

The analysis has so far been based on the assumption that all GHG mitigation in PA host countries takes the form of efficient reductions in fossil-fuel energy use across the entire economy using comprehensive carbon pricing (or carbon taxation). The net economic welfare cost to host countries of such mitigation takes the form of a deadweight loss, found as the net value of the reduced output when fossil-fuel inputs are reduced. An alternative way to reduce fossil-fuel consumption and carbon emissions is through investments in non- or low-carbon infrastructure, for direct replacement of zero-carbon energy for fossil fuels. To consider this alternative, assume that no carbon taxation is used ($t = 0$). Assume that a fraction (1-α) of the energy use in the host economy is replaced with zero-carbon energy (as when zero-carbon energy supplies the entire or part of the electricity sector which previously was based on fossil fuels). We can represent the economy's carbon emissions by its remaining fossil-fuel energy consumption $R_A = \alpha R_B$. Under certainty, we can replace equation (3.1) with

(A1) $$W_1(q) = \alpha\left(R_B - \frac{1}{2}\gamma R_B{}^2 - pR_B\right) + q(R^* - \alpha R_B)\,.$$

The expression in the first bracket on the right-hand side of (A1) represents the net value of the remaining fossil-fuel-based sectors of this economy, and R^* - R_A is now the amount of ITMO net sales (the NDC target minus the host country's GHG emissions). Maximizing (A1) with respect to R_B yields

(A2) $$\alpha - \gamma\alpha R_B - p\alpha - q\alpha = 0 \Leftrightarrow R_B = \frac{1}{\gamma}(1 - p - q)\,.$$

Under uncertainty, with the same probability distribution of the uncertainty variable z as before (uniform distribution on [-z_0, z_0] for the entire economy), and the same basic policy (no ITMO sales unless the probability of NDC deficit is zero), the highest possible fossil energy consumption under uncertainty in the remaining fossil-fuel-driven sector is

(A3) $$R_A = \frac{\alpha}{\gamma}(1 - p - q + z_0)\,.$$

The number of ITMOs sold net is (where $v(inv)/\gamma$ represents ITMOs sold ex ante without possibility of later ITMO purchases, in the case of zero-carbon investments):

(A4) $$\frac{v(inv)}{\gamma} = R^* - R_A = \frac{1-p-s}{\gamma} - \frac{\alpha}{\gamma}(1-p-q+z_0) = \frac{q-s-\alpha z_0}{\gamma} + \frac{1-\alpha}{\gamma}(1-p-q).$$

The relevant comparison with the carbon tax policy case is using the following expression (where *v(tax)/γ* represents ITMOs):

(A5) $$\frac{v(tax)}{\gamma} = \frac{q-s-z_0+t}{\gamma}.$$

The last term in (A4) expresses the expected reduction in GHG emissions due to the sectoral transition to zero-carbon energy, while *v(tax)/γ* in (A5) expresses the same reduction when a carbon tax is instead imposed. When these two policies yield the same GHG emissions reduction, the zero-carbon investment policy yields an additional benefit: higher net forward ITMO sales relative to the carbon tax policy, represented by the factor α before z_0 in (A4). This is because uncertainty is reduced by the investment policy relative to the tax policy, since uncertainty in terms of impacts of mitigation policy is now limited to only the part of the economy which is still based on fossil fuels. With reduced uncertainty, the host needs to "overshoot" its NDC target by less, to assure NDC compliance.[24]

Otherwise, the two cases are very similar when applied to ITMO contracting under the alternatives discussed in section 4.

Appendix 2: Analysis of the Put Option Case (Sub-Section 4.2)

We will now derive analytically the case where host countries have access to put options for selling ITMOs near 2030. This is relevant when a host expects to be in over-compliance in 2030 in at least some states, and no ITMO spot market then exists. We will here initially assume that the host cannot sell ITMOs forward, and will not, in 2030, have access to a spot market with "high" ITMO prices.

[24] The actual difference in uncertainty resulting from these two modes of mitigation could however be smaller than we claim. When a carbon tax is applied to the entire economy, this could also reduce the residual uncertainty related to the remaining emissions at the end point, a factor which we here ignore. Some difference in uncertainty between the modes, of the type pointed out, is still likely to remain.

To recuperate from sub-section 4.2, the uncertain component of the host's GHG emissions rate at the end point, z, is assumed to have a uniform distribution, with $Ez = 0$, with support $[-z_0, z_0]$, and with constant probability density on its support equal to $1/(2z_0)$.

We assume that the host is exactly in NDC compliance in 2030 given the highest possible emissions rate, corresponding to $z = z_0$, which implies:

$$(4.2) \qquad z_0 + s - q - t = 0.$$

We now first compute the host country's expected "excess ex post mitigation" (beyond its NDC target), given that (4.2) holds. This expected excess is found by integrating these reductions, $z_0 - z$, over the uniform distribution from $z = -z_0$, to $z = z_0$, as follows:

$$(A6) \qquad EM = \frac{1}{\gamma}\int_{z=-z_0}^{z_0}(z_0 - z)\frac{1}{2z_0}dz = -\frac{1}{2\gamma z_0}\frac{1}{2}\left(-(2z_0)^2\right) = \frac{z_0}{\gamma} \quad .$$

More simply, the expected excess mitigation equals the average of the minimum excess (zero), and the maximum excess ($2z_0/\gamma$) (which occur when the realized value of z is at its maximum, z_0, and minimum = $-z_0$, respectively). The host here prepares for compliance in the "worst case" ($z = z_0$), as it is assumed not to be able to buy ITMOs later. Greater uncertainty (= larger z_0) leads to more excess mitigation beyond the NDC target at the end point (z_0/γ), and thus greater mitigation costs; but (as seen below) more room for selling ITMOs and thus a greater benefit from such sales when put options are available. In other words, greater uncertainty makes the host country more cautious in its mitigation policy by overshooting its NDC by more in expectation; while it leaves more room for conditional ITMO sales ex post.

The host pays a fixed fee $q_2 > 0$ (ex-ante) for each put option it acquires for selling ITMOs near 2030. The maximal number of ITMOs that the host may wish to sell in 2030 in our case (when (4.2) holds, and the host always stays in NDC compliance) corresponds to its maximal excess mitigation beyond the country's NDC target for 2030, which is $2z_0/\gamma$. The (ex-ante contracted) price per ITMO received by the host when selling ITMOs in 2030 equals q_1, which may equal or differ from the ITMO price for current forward ITMO sales, q. q_1 is here assumed to be constant and exogenous to the host buying put options.

The next step is to compute the lower limit for the distribution of z, over which the host wishes to have a sufficient number of put options to sell its desired number of ITMOs ex post (by exercising purchased put options). This lower limit is called $z_1 > -z_0$. Below this limit, the host country will find it unfavorable to purchase additional put options to realize a maximum amount of ex post ITMO sales. For such lower realizations of z, the number of exercised put options will be a constant, $(z_0 - z_1)/\gamma$, which equals the optimal number corresponding to the realization $z = z_1$. For higher realizations of z, the number of put options that are exercised ex post, will follow the uniform distribution. The ex-ante expected financial gain from selling ITMOs ex post (given this constraint on purchased put options) is then found as

(A7) $$EG(z_1) = \frac{1}{\gamma}\left[\frac{(z_0 + z_1)(z_0 - z_1)}{2z_0} + \int_{z=z_1}^{z_0} \frac{z_0 - z}{2z_0} dz\right] q_1 = \frac{1}{4\gamma z_0}(3z_0^2 - 2z_0 z_1 - z_1^2) q_1 .$$

The first and second main terms in the square bracket here correspond to put options exercised for ex-post values of z below z_1, and above z_1, respectively.

The problem for the host is to maximize the following difference between the value of future ITMO sales ($EG(z_1)$), and the cost of acquiring the required put options:

(A8) $$ES(z_1) = \frac{1}{4\gamma z_0}(3z_0^2 - 2z_0 z_1 - z_1^2) q_1 - \frac{z_0 - z_1}{\gamma} q_2 .$$

Maximizing (A8) with respect to z_1 yields the following optimal value:

(4.3) $$z_1 = -z_0 + 2z_0 \frac{q_2}{q_1} .$$

The number of put options purchased by the host, $v(p)/\gamma$, is given by

(A10) $$\frac{v(p)}{\gamma} = \frac{z_0 - z_1}{\gamma} = 2\frac{z_0}{\gamma}\left(1 - \frac{q_2}{q_1}\right).$$

(A10) gives a highly intuitive expression as the number of purchased put options is a linear function of q_2/q_1, the ratio between the put option cost and its exercise (or strike) price. We find that when $q_2 = 0$ (put options are costless), put options will be purchased for all ex-post realizations of z. When $q_2 = q_1$, no put options will be purchased as there are no gains to holding them.

Whenever $q_2/q_1 < 1$, a fraction of the states, but not all, will be covered with put options regardless of the value taken by q_1. This is because the best possible states for the host (with the lowest values of z) occur with probabilities approaching zero, not giving these states a sufficient weight in this calculation.

To find the welfare effect of having the (ex-ante) optimal quantity of put options available ex post, denoted $EW(p)$, we substitute for z_1 from (4.3) in (A8) which yields:

$$\text{(4.4)} \qquad EW(p) = \frac{z_0}{\gamma}\left(1 - \frac{q_2}{q_1}\right)^2 q_1 + A_1,$$

where A_1 is a constant (independent of the availability of put options). The welfare impact of put option access rapidly falls as the unit ex-post ITMO sale price, q_1, drops toward q_2. This is due to a combination of three separate effects: a unit price effect; a volume effect; and that the ex-ante option cost, q_2, has greater significance when q_1 is low.

The welfare effect is proportional to z_0, which represents the spread of the uniform distribution. Higher spread implies higher excessive mitigation and thus higher mitigation costs; this is (partly) countered by higher availability of ex-post ITMO sales via put options.

Extension 1: Uncertain Realization of Put Options

Consider an alternative case where the host may no longer be able to always exercise its purchased put options. Assume a (constant) probability, $\theta < 1$, that all put option trades can be exercised ex post, and a probability $1-\theta$ that the put options, after having been purchased, cannot be exercised. These probabilities are independent of the number of put options held.

The ex-ante expected financial gain from selling ITMOs ex post is in this case found by multiplying the gain specified in (A7) with the trading probability θ:

$$\text{(A11)} \qquad EG(z_1;\theta) = \frac{\theta}{4\gamma z_0}(3z_0^{\,2} - 2z_0 z_1 - z_1^{\,2})q_1 .$$

The host's problem is also here to maximize the difference between the expected value of future ITMO sales, in this case $EG(z_1;\theta)$, and the cost of acquiring the put options, with respect to z_1:

(A12) $$ES(z_1;\theta) = \frac{\theta}{4\gamma z_0}(3z_0{}^2 - 2z_0 z_1 - z_1{}^2)q_1 - \frac{z_0 - z_1}{\gamma}q_2 .$$

This now yields:

(A13) $$z_1 = -z_0 + 2z_0 \frac{q_2}{\theta q_1} .$$

The number of put options purchased by the host, *v(p)*, is now given by

(A14) $$v(p) = 2\frac{z_0}{\gamma}\left(1 - \frac{q_2}{\theta q_1}\right).$$

A drop in the trading probability θ here has the same impact on the number of put options bought, as a drop in the ex-post ITMO sales price, q_1. As expected, the number of put options purchased ex ante by the host drops as θ is reduced. When θ drops sufficiently so that $q_2 = \theta q_1$, no put options will be purchased by the host country.

There are two compounding effects of a reduction in θ on the number of ITMOs sold ex post by the host. The first is the direct reduction due to a higher probability that the options cannot be exercised. The second is the (more indirect) effect from fewer put options being purchased ex ante, which reduces ex-post ITMO sales also when the acquired put options can be exercised.

The optimized welfare impact of available put options is:

(A15) $$EW(p) = \frac{z_0}{\gamma}\left(1 - \frac{q_2}{\theta q_1}\right)^2 q_1 + A_1 .$$

This welfare level also drops, and "faster" in θ than the number of ITMOs sold. A further compounding effect is that put option costs per expected ITMO exercised increases when θ drops.

An issue not so far discussed is whether compensatory payments are made by the option issuer to the purchasing host in case of a breach of contract, so that purchased put options cannot be exercised. Such compensatory payments will reduce the real cost of the put options to the purchasing host, limit the reduction in the number of purchased put options, and limit the resulting welfare loss to the purchasing host country.

Extension 2: Positive Probability of Ex-Post Access to ITMO Sales at High Price

The second extension considers a positive ex-ante probability that the host will face an ex-post spot market for ITMOs with a "high" ITMO market price, exceeding q_I. It should here first be commented that our three options alternatives, in sub-sections 4.2-4.5 (and Appendices 2-5), are based on the assumption that no spot market for ITMOs is open near 2030. It may seem more plausible to assume that such a market might, ex ante, be anticipated to exist with a positive (perhaps small) probability. In cases where spot markets for ITMOs with prices higher than q_I are open near the PA end point, the host will choose to not exercise its put options but instead sell ITMOs in the spot market at this higher price. Assume that this higher future selling price, called q_H, occurs with probability 1-λ, while the put option alternative will be exercised with probability λ. Assume that these probabilities are independent of z.[25] The only aspect of the above analysis that would change is that now q_I in (A7) - (A10) and (4.3) is replaced by λq_I. The number of put options purchased by the host, from (A10), will be reduced, as they are now less valuable (they are exercised in fewer states). With probability 1-λ, put options are now not necessary and thus not desirable as the host's excessive ITMOs will be sold in the spot market. Welfare of the host will be higher, but the welfare contribution from put options will be reduced.

The impact in our model for the host's optimal choice of put options holdings is the same here as under extension 1 (substituting λ for θ). The benefit to the host of holding put options is the same in the two cases. What is different is welfare for the host when put options are not exercised, which is (far) higher in the current case than under extension 1.

Note that our model is extremely simple in some aspects. In particular, the host's mitigation policy (including carbon tax), and total sale of ITMOs, are the same in both cases. Perhaps a higher carbon tax and higher ITMO sales will be chosen under extension 2. Also, both probabilities λ and θ are assumed to be independent of z (the uncertainty for the host), which may not be the case (see footnote 25).

[25] These probabilities could be correlated. There could in particular be positive correlation between λ and z: When the host's demand for ITMOs in the ex-post market is high (which occurs when z is high), the ex-post ITMO price is more likely to be high. Positively correlated z values would lead to such a situation. This is likely to happen, for example, when the global economy is in a "boom" or "bust" situation near 2030; or when global mitigation in 2030 is strongly affected by technical breakthroughs for zero-carbon technologies.

Appendix 3: Analysis of Call Options for ITMO Sellers (Sub-Section 4.3)

We will now provide a more detailed analytical treatment of the case in sub-section 4.3, where host countries are given the option to sell ITMOs forward, and cover themselves with call options providing the opportunity to buy ITMOs back at or near the end point (2030), if needed for compliance.

The host's NDC target is assumed to be given by (3.4), and its mitigation level at the end point by (3.2). This corresponds to an increase in ITMO sales from (3.4), which leads to an increased shortfall of mitigation toward the NDC target, as ITMO sales weaken the host's NDC compliance. The net contribution toward the NDC target in terms of the host's GHG emissions plus the ITMOs sold is denoted by -R^{**}, from:

(A16)
$$R^{**} = \frac{1-p-q-t+z+v}{\gamma}.$$

NDC compliance of the host country requires $R^{**} \le R^{*}$, which implies

(A17)
$$z \le z_1 = q+t-s-v \ .$$

For values of z exceeding z_1, the host will not be NDC compliant in 2030 given its forward ITMO sales from (3.6), when the host exercises no call options nor resorts to "backstop" mitigation. We assume that $z_1 < z_0$ (otherwise, the host would always be NDC compliant and no call options for ex-post purchase of ITMOs would be required). With a uniform distribution of z with support [$-z_0$, z_0], the probability of the host being non-compliant is $1 - F(z_1)$ given by

(A18)
$$1-F(z_1) = \frac{z_0 - z_1}{2z_0}$$

We can now compute the expected mitigation shortfall in 2030, *ES*, which requires the host to use call options to purchase ITMOs back. For realizations of z beyond z_1, a mitigation deficit $(z - z_1)/\gamma$ must be made up by exercising call options.

The expression for the expected mitigation shortfall, relative to the host's NDC target in 2030, is (substituting in the last expression for z_1 from (A17))

(A20) $$ES = \frac{1}{\gamma} \int_{z=z_1}^{z_0} (z - z_1) \frac{1}{2z_0} dz = \frac{(z_0 - z_1)^2}{4\gamma z_0} = \frac{(z_0 + s + v - q - t)^2}{4\gamma z_0} \quad .$$

For the host to stay in compliance in 2030, the shortfall in (A20) must be countered by exercising call options. Assume that the unit cost of purchasing ITMOs back when exercising call options is q_3, which is determined when call options are contracted ex ante. Assume that $q_3 \geq q$: It cannot be cheaper for the host to contract a buy-back of ITMOs at the end point, than the price the host obtains from selling ITMO contracts forward ex ante.[26] This cost must be added to the cost of having (certain) access to a sufficient number of call options to stay in compliance in all possible states, which is q_4 per call option. Assume that q_4 is constant and independent of the volume of call options purchased. The number of call options that the host country is required to hold equals the largest possible mitigation shortfall ex post. This here corresponds to a realization z_0 of the stochastic variable z (the "worst possible" outcome from the host country's point of view).

Welfare of the host country can be expressed in terms of expected emissions, ER_1, and the variables affected by forward ITMO sales:

(A21) $$EW_1(q) = ER_1 - \frac{1}{2}\gamma(ER_1)^2 - pER_1 + q\frac{v}{\gamma} - q_4 \frac{z_0 - q - t + s + v}{\gamma} - q_3 \frac{(z_0 - q - t + s + v)^2}{4\gamma z_0} .$$

The three first terms of (A21) express the net expected economic return from an economic activity that employs an emissions level given by the employed carbon tax. In this exercise we hold ER_1 fixed as we assume that the host only uses forward ITMO sales as basis for its optimal purchase of call options, and keeps its carbon tax t fixed.[27] Maximizing (A21) with respect to v/γ then yields[28]

(4.6) $$\frac{v}{\gamma} = \frac{q + t - z_0 - s}{\gamma} + \frac{2(q - q_4)z_0}{\gamma q_3} \quad .$$

[26] The ITMO price q_3 when exercising call options could however also be uncertain if not contracted directly. Here we assume that the options contract specifies a fixed price. See below for a discussion of extended cases.
[27] This is not obvious. Purchasing call options could instead lead to a reduction in the host's own GHG mitigation activity by lowering its carbon tax, t; which may occur when t is initially high. Such a case is considered in sub-section 3.4 and Appendix 4.
[28] ER_1 is here constant as v/γ does not affect current (ex-ante) emissions in this case, only the need to purchase back ITMOs later. This is different from ER_2 in (A17) below, where v/γ directly increases current mitigation through an adjustment in the carbon tax t.

Assume next that the host chooses t to always fulfill (4.2), staying exactly in NDC compliance in its highest emissions state ($z = z_0$). The first main term on the right-hand side of (4.6) drops, and the solution for forward ITMO sales equals the number of call options purchased:

$$\frac{v(c)}{\gamma} = \frac{2(q - q_4)z_0}{\gamma q_3} \quad . \tag{4.7}$$

When $z < z_0$, the country's GHG emissions level is, from (3.6) and (4.2),

$$R_1 = \frac{1 - p - s - (z_0 - z)}{\gamma} \quad . \tag{4.8}$$

A positive ITMO sales amount given by (4.7) here brings the country out of NDC balance (due to the necessary CA), but is brought back into balance by purchasing the same number of call options, to enable purchasing ITMOs back ex post when necessary.

Optimized net welfare, $EW_1(opt)$, from access to the call options (with equivalent increase in forward ITMO sales) is found by inserting for $v(c)$ from (4.7) in (A21):

$$EW_1(opt) = \frac{(q - q_4)^2 z_0}{\gamma q_3} + A_2 \ , \tag{4.9}$$

where A_2 is a constant. As in the put option case, welfare from optimized call option purchases combined with optimal forward ITMO sales is proportional to the distributional spread, z_0. It is proportional to the square of the net unit value of selling ITMOs forward, $q - q_4$, and inversely proportional to the cost of ITMO buybacks ex post, q_3.

Two potential problems with the market for such call options are: a) ex post purchase of ITMOs on the basis of call options may sometimes require payment of an extra premium on top of the contracted ex post price q_3; and b) options may not be exercised as the option issuer reneges on the promise to deliver.

Case a can, under some assumptions, easily lend itself to analytical treatment. One such case is where q_3 is stochastic but all necessary ITMOs are still exercised, for the host to be able to stay in NDC compliance at the end point. In the simplest such case, q_3 can be replaced by Eq_3 in (4.7) and (4.8). When the host then has access to backstop mitigation at cost r, this cost will cap the effective price distribution for q_3.

Case b can create a more fundamental problem as the host may then not reach its NDC target (given no spot market nor available backstop option in 2030).

Extension: Positive Probability of Ex-Post Access to ITMO Purchases at Low Cost

Similar to Appendix 2, we consider also in this case an extension to a case with positive probability of a well-functioning spot market where ITMOs can be purchased; but now at a low (not high) cost, below q_3. Assume that this occurs with ex-ante probability $1–\sigma$, while the probability that no favorable spot market will exist is σ. Assume still that z is not correlated with the probability of an ex-post ITMO spot market. Then this extension can be represented very simply, by replacing q_3 with $\sigma q_3 + (1-\sigma)q_L$, where q_L is the (low) spot market price for ITMO purchases ex post.

The number of call options purchased is then

$$\text{(A22)} \qquad \frac{v(c;q_L)}{\gamma} = \frac{2(q-q_4)z_0}{\gamma[\sigma q_3 + (1-\sigma)q_L]} > \frac{v(c)}{\gamma} \ .$$

The likelihood of a favorable ex-post spot market for ITMOs (favorable to hosts needing to *buy* ITMOs ex post; thus, with a *low* ITMO price) here *increases* the number of (call) options purchased by the host country. This differs qualitatively from the impact of a similar additional market access in the put options case, which in that case was to *reduce* the number of options purchased. The qualitative difference between these two cases is that in the put options case, there is no relation between the number of options purchased ex ante, and ITMOs to be sold ex post when an ex-post spot market for ITMOs is open. In the current case there is such a direct relation: The number of ITMOs needed to be purchased back ex post in the spot market, to always remain in NDC compliance, is identical to the number of ITMOs purchased back using call options. One here thus needs to consider the average profitability of ITMO buybacks, by either of the two mechanisms, which was not the case in Appendix 2.

Appendix 4: Analysis of Call Options for ITMO Buyers (Sub-Section 4.4)

We now assume that the country in question only purchases call options as an insurance against uncertainty about ex post NDC compliance, and cannot purchase ITMOs ex post. As different from Appendix 3, we now consider an “ambitious” host where s, indicating the ambition of the party’s NDC, is high. This party does not sell ITMOs forward, but may instead want to keep its carbon tax at the lowest possible level required to always be NDC compliant, and use call options to cover any possible ITMO deficit in 2030. Welfare of the ITMO buyer can then be expressed as follows, in terms of expected emissions, ER_2, and the costs related to the purchase of call options plus the future expected cost of exercising these options:

(A23) $$EW_2 = ER_2 - \frac{1}{2}\gamma(ER_2)^2 - pER_2 - q_4\frac{v}{\gamma} - q_3\frac{v^2}{4\gamma z_0}.$$

We consider the case where this party (now a net ITMO buyer) is exactly in NDC compliance when z takes its highest possible value ($= z_0$), when the host has no net forward ITMO trade, and purchases no call options for future ITMO purchases. In this case, the two terms in (A23) which represent call options costs can be simplified relative to (A21), so that the first main term on the right-hand side of (4.6) drops out.

Assume, as in Appendix 3, that this party has no access to a future spot market for buying ITMOs in 2030, but can buy call options for future ITMO purchases. ER_2 can then be expressed as

(A24) $$ER_2 = \frac{1-p-t-q}{\gamma} = \frac{1-p-s-z_0+v}{\gamma}.$$

In the case considered, $t = s + z_0 - q - v$, which means that when the number of call options, v/γ, is increased, the party's carbon tax can be reduced equivalently, and this party's deadweight loss related to the carbon tax is reduced.

v/γ then also represents the excessive emissions rate (beyond the rate that keeps the country exactly in compliance for certain without access to future call options), which must be compensated with the purchase of call options to make sure that the host stays in compliance. This implies that when the country purchases call options, the initial climate policy is relaxed equivalently by reducing t. Inserting this into (4.1) and taking the derivative with respect to v yields the following condition for optimal call options purchases by a net ITMO-buying host:

(A25) $$\frac{dEW_2}{dv} = \frac{1-p}{\gamma} - ER_2 - \frac{q_4}{\gamma} - \frac{q_3 v}{2\gamma z_0} = 0.$$

The two first terms in (A25) come in addition to (4.6), the equivalent expression in Appendix 3.

The solution for the optimal number of call options purchased is

(A26)
$$\frac{v(c)}{\gamma} = \frac{2(z_0 + s - q_4)z_0}{\gamma(2z_0 + q_3)}.$$

Welfare is in this case:

(A27)
$$EW_2^* = \frac{(z_0 + s - q_4)^2 z_0}{\gamma(2z_0 + q_3)} + A_3,$$

where A_3 is a constant. We see that when s is large relative to z_0, the change in welfare, relative to the case with no call options contracts, is greater in (A27) than in (3.8). It is then better for the host to reduce its initial emissions rate than selling ITMOs forward.

A difference between the current case and that in sub-section 4.3 (and Appendix 3) is that in sub-section 4.3, the relevant party was assumed to go "out of initial NDC compliance" by selling ITMOs forward. This host is here assumed to not take a net trade position in the forward ITMO market. It instead goes "out of compliance" by increasing its GHG emissions by $v(c)/\gamma$. This is done by relaxing its carbon tax t equivalently; later compliance is then assured by purchasing call options. This is beneficial for the host country for two reasons: lowering its carbon tax is beneficial (thus reducing its economic deadweight loss); and holding call options is an economical way for the host to meet possible NDC under-compliance under uncertainty. This is particularly beneficial for a party that selects an ambitious NDC target (has a high value of s), which is more typical for high-income than for lower-income countries. In formulas (A26) and (A27), a high s leads to many call options being purchased, and a high positive welfare effect of such purchases.

A strategy not considered, relevant for a party that is a net buyer of ITMOs, is to reduce its own GHG mitigation further by reducing its carbon tax by even more, below the rate given by (A24), and cover its ITMO compliance by purchasing additional ITMOs forward. In equilibrium for the overall ITMO market, one group of parties must be net buyers of forward ITMO contracts. High-income countries are likely to dominate this group.

Extension: Positive Probability of Ex-Post Access to ITMOs at Low Cost

Consider an extension of this case which corresponds closely to extension 2 in Appendix 3. The host is now aware ex ante that an ITMO spot market, with a "low" purchase price, $q_L < q_3$, may be available in 2030 with probability 1-σ, where $0 < \sigma < 1$. As in Appendix 3, acquired call options will then be exercised with ex-ante probability σ, and will not be exercised with probability 1-σ.

The effect on host behavior is very similar to what was found in Appendix 3. We need to replace q_3 with $\sigma q_3 + (1-\sigma)q_L$, in (A23). The new condition for optimal call options purchases is

(A28) $$\frac{v(c;q_L)}{\gamma} = \frac{2(z_0 + s - q_4)z_0}{\gamma[2z_0 + \sigma q_3 + (1-\sigma)q_L]}.$$

We find that $v(c; q_L) > v(c)$ from (A26). More call options are purchased, despite call options being exercised in fewer states. Intuitively, the availability of cheaper ex post ITMO access in some states (with ex-ante probability 1-σ) leads this host to further reduce its carbon tax, and increase its ex-post ITMO purchases. This requires more call options to stay in NDC compliance for certain, when ITMOs are acquired ex post by exercising purchased call options.

Appendix 5: Analysis of Ex-Post ITMO Deficit Covered by "Backstop" Mitigation (Sub-Section 4.5)

We now consider, similar to Appendix 3, a host which has the interest to sell ITMOs forward, but does not have access to an options market nor ex-post spot market for ITMO purchases. This host needs to cover any late-period ITMO deficits by resorting to (expensive) "backstop mitigation". The maximization problem for the host can in this case be formulated in basically the same way as relation (A21) for the call option case (see Appendix 3). The following simple relation is maximized by the host:

(A29) $$R_{ES} = \frac{qv}{\gamma} - \frac{r}{4\gamma z_0}(z_0 + s + v - q - t)^2.$$

The second main term on the right-hand side of (A29) corresponds to the similar term in (A21). Maximizing R_{ES} with respect to the number of ITMOs sold forward, v/γ, yields:

(A30) $$\frac{dR_{ES}}{dv} = \frac{q}{\gamma} - \frac{r}{2\gamma z_0}(z_0 + s + v - q - t) = 0.$$

The general expression for optimal forward ITMO sale, $v(b)/\gamma$, is here

(A31) $$\frac{v(b)}{\gamma} = \frac{q+t-z_0-s}{\gamma} + 2\frac{qz_0}{\gamma r}.$$

ITMOs sold forward, given that (4.2) holds ($z_0 + s - q - t = 0$), equals the amount of backstop mitigation, *m(b):*

(A32) $$\frac{v(b)}{\gamma} = m(b) = 2\frac{qz_0}{\gamma r}.$$

GHG emissions are here determined in the same way as in Appendix 3.

Optimized net welfare is found by inserting for *v(b)* from (A32) in (A29):

(A33) $$W_{ES}^* = \frac{q^2 z_0}{\gamma r} + A_4,$$

where A_4 is a constant independent of using the backstop alternative. The expression for the net welfare impact of access to a backstop option (given a unit backstop cost r) takes a form very similar to the forms found for put and call options, (4.4), and (4.9). Welfare is proportional to our uncertainty measure, z_0; increases in the ratio of the forward ITMO price to the backstop cost, q/r; and the backstop price becomes less significant when q rises. On the other hand, the incentive for the host to fail to apply backstop mitigation ex post is likely to increase in r.

List of abbreviations used in the paper

BAU = Business-As-Usual

CA = Corresponding Adjustment

CDM = Clean Development Mechanism (under the KP)

CIF = Climate Investment Funds

GCF = Green Climate Fund

GHG = Greenhouse Gas

IFI = International Financial Institution

ITMO = Internationally Transferred Mitigation Outcome (under the PA)

JI = Joint Implementation (under the KP)

KP = Kyoto Protocol

MAC = Marginal Abatement Cost

NDC = Nationally Determined Contribution (under the PA)

PA = Paris Agreement

PAF = Pilot Auction Facility

TCAF = Transformative Carbon Asset Facility

VER = Verified Emissions Reduction (under the KP)