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Transformational Climate Finance

Donors' Willingness to Support Deep and Transformational Greenhouse Gas Emissions Reductions in Lower-Income Countries

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Abstract

This paper uses simple analytical models to study high-income donor countries' willingness to pay to supply mitigation finance to low-income countries; how this depends on modality for finance supply; and how it changes as the global greenhouse gas mitigation agenda moves forward. The paper focuses on two modalities: transformational project-based mitigation finance (transitioning from fossil to non-fossil energy use at scale), and transformational policy-based mitigation finance support (implementing comprehensive carbon taxation). These modalities are compared with conventional finance for which donors have lower willingness to pay. High-income countries' willingness to pay is higher when mitigation is combined with carbon taxation; private-sector finance is also more highly incentivized. Reaching the transformational mitigation finance stage can be challenging, as it may require large provision of mitigation finance with negative net returns to high-income countries. Willingness to pay will be higher when high-income countries collaborate in the provision of mitigation finance. The findings show that more effective collaboration can be sustained when it is enforced by an international financial institution that collects and spends the provided mitigation finance to induce efficient mitigation activity in low-income countries and collaboration among donors is enforced by simple tit-for-tat reaction strategies.

Transformational Climate Finance: Donors' Willingness to Support Deep and Transformational Greenhouse Gas Emissions Reductions in Lower-Income Countries[*]

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1. Introduction

This paper focuses on mobilizing mitigation finance (MF) for increased greenhouse gas (GHG) mitigation in World Bank client ("lower-income", hereafter L) countries, and studies the interest and ability of high-income (H) donor countries to supply such finance. Among key questions raised are:

• What incentives do H countries have to provide MF to L countries; in other words, what is the "willingness to pay" (WTP) of H countries to supply MF?

• What is H countries' ability to actually mobilize MF for L countries?

• How effective is MF at reducing GHG emissions in L countries; and what factors determine this effectiveness?

These questions are topics of recent and ongoing analytical work, in the World Bank and elsewhere.[1] The intent of this paper is to address them at a more formal analytical level.

A basic premise throughout the paper is the presence of a *positive WTP in H countries to finance greater GHG mitigation in L countries*. GHG mitigation in any country is a global public good that provides benefits to countries at all income levels. We focus on the way that H countries' WTP to support MF depends on what mitigation programs are implemented in L countries, their economic efficiency, and their mitigation impacts. A key emphasis in the paper is the importance of MF support to programs and policies in L countries that can be (very) expensive and/or difficult to implement, but have large, deep and long-lasting ("transformational") impacts on GHG emissions in the countries receiving this finance.[2] We will also study the degree to which such transformational developments are driven by additional factors including technological change in the energy sector; private financing leveraged by donor MF financing; and carbon pricing in L countries.

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[1] See also Gonzalez 2008; Audoly et al. 2014; Engle et al. 2018; Rozenberg and Fay 2018; and Stretton 2019, 2020.
[2] Part of the analytical discussion of H countries' WTP to provide MF, in sections 3-6 and Appendixes 1-3, is based on model frameworks developed in Strand 2013, and Mundaca and Strand 2019, 2020.

We will throughout, for simplicity of analysis and exposition, assume that donors are non-altruistic. We assume that: a) donors care about increased L country mitigation as long as it reduces global GHG emissions (benefitting also H countries); b) H countries do not explicitly care about other positive outcomes resulting from mitigation finance in L countries, such as improved development and welfare; and c) H countries do not provide financial support to climate-related adaptation activity in these countries.[3]

We focus on three broad modalities through which H country MF provision supports GHG mitigation in L countries:

"*Non-transformational, project-based MF*": Support to individual mitigation projects, mainly as a benchmark against which efficiency of the other modalities can be compared (see section 3 of the paper).

"*Transformational, project-based MF*": broader-based programs to overcome barriers to low-carbon transition, as discussed in Engle et al 2018 (see section 4).

"*Transformational, policy-based MF*": broad-based mitigation-inducing policies, with particular focus here on comprehensive carbon taxation (see section 5).

While the first (non-transformational) modality has been dominant for donor supported GHG mitigation in L countries to date, the two transformational modalities are likely to play major roles going forward under the 2015 Paris Agreement (PA) for global GHG mitigation, and beyond. Broad-based carbon pricing is likely to be a very important element in future climate policy regimes, combined with transformational project-based MF funding.[4] We show that the WTP of H countries to provide MF depends on how these two modalities are applied, alone or in combination; and that WTP of H countries to provide MF to L countries can vary substantially with particular circumstances for any given modality.

The development from a non-transformational to a transformational phase is set out, rather schematically, in section 2. We assume the existence of increasing returns to scale in overall

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[3] This assumption is made to sharpen our focus on mitigation finance, and with little loss of generality for this presentation. Donors have, in reality, of course concern for the welfare of L countries, and do provide adaptation finance to L countries; albeit to differing degrees.

[4] See e g Wooders et al. 2016; Steckel et al. 2017; Black et al. 2018.

mitigation, and thus in provision of MF, leading to "low" and "high" equilibria for MF that correspond to those phases. After discussions of the three modalities listed above in sections 3-5, section 6 analyzes the potential for increased donor MF via contributions to a coordinating institution (e.g., an IFI). We show that such coordination can greatly increase donors' WTP for MF, thus facilitating reaching the transformational MF range.

We will say little about "results-based" climate finance (RBCF) and other conditional finance forms for international MF.[5] RBCF (and policy conditionality) will however be important in our discussion of domestic carbon tax implementation in L countries. The "Unconditional Nationally Determined Contributions" (NDCs) of L countries (these countries' own plans for mitigation action under the Paris Agreement, PA) are taken as given starting points for L countries' own mitigation action activity.

2. Simple framework for conceptualizing "transformational MF"

Most L countries are not yet close to the point of readily undergoing transformational change of their energy sectors, by large-scale adoption of non-fossil energy sources and technologies. We will in this section present a highly stylized model to illustrate a possible transition to a "transformational MF" stage starting from today's situation. This model ties together the analytical parts that follow, "non-transformational project MF' in section 3; "transformational MF" in sections 4-5; and donor collaboration in section 6.

Consider GHG mitigation taking place in an L country or group of L countries, financed in part by MF supply from one or more H countries. Figure 1 presents two curves, both reflecting an H country view. Q is the level of MF supplied by the respective H country or group of H countries. One curve shows the marginal cost (to H countries) of supplying MF for such activity (the marginal cost, MC, curve). It slopes upward for reasons noted below. The other curve ("return to mitigation finance", RMF) gives the marginal return to additional GHG mitigation finance for donors. It represents a monetary measure of their potential future losses from climate change that are avoided by increased mitigation in L countries.

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[5] For discussion of RBCF see Differ Group 2016, World Bank, Ecofys and Vivid Economics 2017, World Bank and Frankfurt School of Finance and Management 2017, and Engle et al. 2018.

Figure 1: Value and cost of MF provision for donors
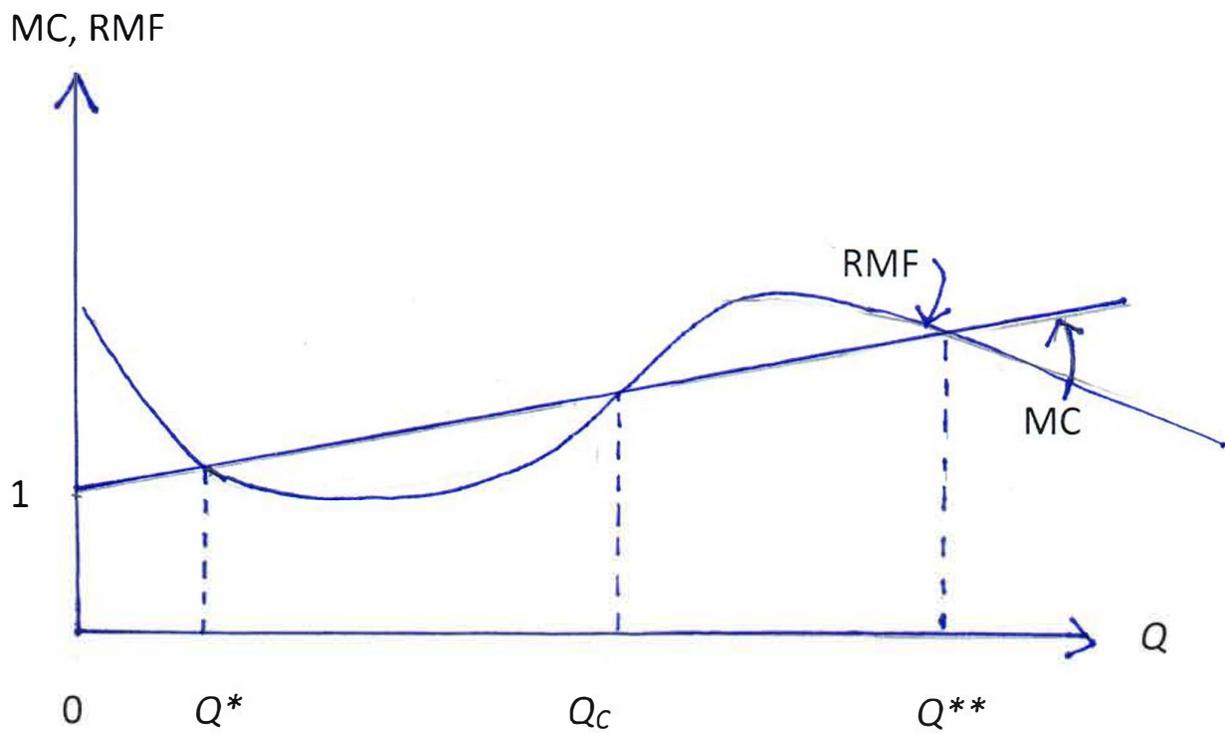
RMF = marginal return to Mitigation Finance
MC = marginal cost of providing Mitigation Finance

An H country's objective function is assumed to take the form

$$(2.1) \qquad W = v_H e(Q_E)Q - (Q + \frac{1}{2}\sigma Q^2).$$

In (2.1), the parenthetical expression represents the H country's cost of providing MF. Donors are assumed to be increasingly averse to providing more resources for GHG mitigation in L countries, for political and/or fiscal reasons.

The first term in (2.1) is the monetary benefit for an H country of providing the quantity Q of MF. v_H is the monetary value per unit of GHG mitigation, while the $e(...)$ function expresses the amount of mitigation incentivized per unit of MF. This mitigation per unit of MF likely depends on the amount of MF provided by all donors, for reasons discussed below. An individual H country will have an expectation of the per-unit mitigation obtained from its MF, denoted in (2.1) by $e(Q_E)$. Assuming these expectations are realized, then the sum of all H countries' MF will lead to a per-unit mitigation impact consistent with the effects of all MF provided. But this function can also be interpreted as (partially) representing cumulative past MF contributions, for example to R&D efforts in the energy sector. This is a particularly relevant interpretation when MF is being ramped up gradually over time, simultaneously by all donors, and "mitigation effectiveness" is being impacted both by the current MF supply, and by the cumulative past supply of MF to R&D development, with its positive impact on the e function.

The first-order condition with respect to MF for maximizing W in (2.1) is:

$$(2.2) \qquad v_H e(Q_E) - 1 - \sigma Q = 0 \Leftrightarrow v_H e(Q_E) = 1 + \sigma Q.$$

$1 + \sigma Q$ (= MC) is the marginal finance cost for the H country. The term $v_H e$ (= RMF) is an H country's marginal return to MF.

A key for motivating the difference between transformational and non-transformation MF lies in the assumed shape of the e function shown in Figure 1. The e function starts (for $Q \cong 0$) at a relatively high level, to reflect "low-hanging fruits" in mitigation, meaning opportunities for significant mitigation at relatively low outlay. The per-unit mitigation then falls as those immediate opportunities are used up. This is what happens in the "non-transformational project MF" phase, discussed in section 3 below.

We assume in Figure 1 that as Q continues to increase, the e function starts rising again before again declining. This represents the move into the "transformational" phase of MF, with larger-scale mitigation in L countries as the quantity of MF rises, and higher technical efficiency of MF as a result of past R&D efforts. This functional shape corresponds closely to the concept of "minimum efficient scale" for mitigation in Grubb (2014). One rationale for this is that there is a minimum level of mitigation either within or across countries, and for energy R&D, that is necessary for deploying lower carbon technologies with economies of scale, e.g., solar power generation across a variety of areas, tied together with a smart grid, to increase the likelihood of sufficient sunlight across the system to generate higher quantities of electricity relative to installed capacity. Another rationale is that at larger scales of mitigation, involving more novel technologies (for example, concentrated solar power with storage), there are more opportunities for learning by doing across different operating circumstances and the unit cost of generation falls, implying more mitigation per unit of MF.[6]

As shown in Figure 1, the model with this assumed shape for the e function has two stable equilibria for Q, namely Q^* and Q^{**}. In both cases a falling marginal returns curve to MF ($v_H\,e$) intersects from above with a rising MF marginal cost curve with slope $1+\sigma Q$. One of these equilibria has a low (non-transformational) MF supply, Q^*; and the other a high (transformational) MF supply, Q^{**}. Reaching the high equilibrium requires a concerted effort by donors to increase Q beyond the range between Q^* and Q_C, where marginal MF return to donors is below marginal cost. Once Q has moved past the "tipping point" Q_C, a new stable equilibrium will eventually be reached at Q^{**}. When Q is on the domain between Q_C and Q^{**}, the value to donors of supplying more MF is higher than its cost.

As discussed also above, the phase of increasing returns in Figure 1 will depend on both *current* and *accumulated* MF supply. Broader-based, larger mitigation action is likely to require larger-scale and long-term R&D efforts, as well as scaled-up low-carbon investment programs that also reduce the costs of non-fossil energy technologies and high involvement of the private sector

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[6] Many extensions and generalizations of this framework may be considered. Realistic extensions could be to introduce stochastic "tipping point" Q_C and $v_H\,e$ curves (both of which are unknown), and a smoother transition to the upscaling of low-carbon technology supply (where the supply cost varies across supplied elements).

(supplying most of the finance relevant for mitigation), in response to increases in public MF "transformational" levels toward the "tipping point", Q_C, and beyond.

We do not develop here a formal analysis of the processes by which raising MF past the tipping point might be accomplished. However, the discussion of carbon tax implementation in section 5, and of donor coordination in section 6, point to two separate pathways through which increased WTP by multiple donors can increase total MF provided, and which together can work even more effectively. More robust carbon pricing will lift the e function, in particular by incentivizing the private sector to contribute more to MF-related investments. Donor coordination will, as shown in section 6, contribute to lifting the v_H value by broadening the base for valuing the global impacts of MF. Public returns to supplied MF could then be lifted beyond the "tipping point", Q_C, where returns exceed MF costs, creating a self-sustaining MF increase from then on.

We are not incorporating in our discussion any development benefits to individual L countries from their own mitigation action. Realistically, these will be part of the equilibrium outcome for mitigation and international MF, certainly as one approaches (and reaches) the transformational stage. Such added development benefits will provide greater value of MF to L countries.

3. Donors' WTP to supply "non-transformational project-based MF"

We will in sections 3-5 leave the "birds-eye perspective" of section 2 and focus on a more micro-based analysis of elements to fit into the broader analysis of section 2. We start in this section with studying donor WTP for MF support to GHG emissions reductions from free-standing, individual mitigation projects in L countries, which are not considered as part of a transformational climate policy development. In Figure 1, this refers to "low-hanging fruits" at the left of the figure, "harvested" as one reaches the "low-level" equilibrium $Q*$.[7] We consider this modality to play a limited role under the PA. Such an analysis can still be instructive as a benchmark for comparison with other, more transformational, mitigation action programs, discussed in later sections.

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[7] In sections 3-5, a difference from Figure 1 is that we here assume a constant unit marginal cost of MF supply for donors. Figure 1 instead describes this marginal supply cost as a rising function of the total MF supply, *Q*; more of a long-term macro-type picture. Sections 3-5 focus more on smaller "steps" of this development where a broader macro picture is less required.

Consider the behavior of H countries supporting MF for L countries in this case.[8] The welfare function related to fossil-fuel consumption in the L country, in the absence of MF support from the outside, is specified as:

(3.1)
$$W_L = R_L - \frac{1}{2}\gamma R_L^2 - (p + v_L)R_L.$$

R_L is fossil-fuel consumption in carbon-equivalent units in this country, γ is a fixed technology parameter, p = the fossil fuel price, and v_L = the "co-benefit" to the L country from reducing its carbon emissions from its own mitigation policy.[9] (3.1) represents a simple "linear-quadratic" relationship (where utility or profit for the L economy is a function of fossil fuel consumption only), valid over a (limited) range for R relevant here, and resulting in simple results in particular for cases with small or moderate changes in GHG emissions.[10] (Under the PA, even conditional mitigation targets are for most L countries likely to be implemented using moderate carbon prices, at least in the starting phases.)

The optimal fossil-fuel consumption of the L country before receiving MF from donor countries is found from maximizing (3.1) with respect to R_L:

(3.2)
$$\frac{dW_L}{dR_L} = 1 - \gamma R_L - (p + v_L) = 0 \Leftrightarrow R_L = \frac{1-p}{\gamma} - \frac{v_L}{\gamma}.$$

The L country is assumed to itself implement a mitigation level v_L/γ as part of its unconditional NDC plan, by imposing its own national carbon tax v_L.

Consider an H country or country bloc, which provides MF payments to an L country.[11] Define R_{LC} as the optimal fossil fuel consumption in the L country, given support payments from the H country to the L country in return for additional GHG mitigation. Due to a "missing additionality" problem, discussed below, support payments are however assumed to go also to units of mitigation

[8] The presentation of analytical examples builds largely on Mundaca and Strand 2019a.
[9] Such co-benefits could be significant (see Nemet et al. 2010; Jiang et al. 2013; Parry et al. 2015; Rao et al. 2016, 2017; Pigato et al. 2019).
[10] Mathematically, (3.1) represents a second-order Taylor expansion of the country's net production function, highly precise for small changes in outcome variables but often less precise for larger changes.
[11] We say nothing about how a "country bloc" (or "climate club"; Nordhaus 2015) is conceptualized or formed.

that are implemented through the L country's own carbon tax at level v_L. The L country's objective function can then be formulated as

$$(3.3) \qquad W_{LC} = R_{LC} - \frac{1}{2}\gamma R_{LC}^{2} - (p + v_L)R_{LC} + q_{LC}(R_{L0} - R_{LC}).$$

(3.3) is maximized by the L country with respect to R_{LC}, while R_{L0} is the "business-as-usual" (BAU) GHG emission rate of the L country ($= (1-p)/\gamma$). The H country pays q_{LC} to L countries per emission reduction below R_{L0}.

The optimal fossil energy consumption of country L is found by setting the derivative of W_{LC} with respect to R_{LC} in (3.3) equal to zero:

$$(3.4) \qquad \frac{dW_{LC}}{dR_{LC}} = 1 - \gamma R_{LC} - (p + v_L + q_{LC}) = 0 \Leftrightarrow R_{LC} = \frac{1}{\gamma}(1 - p - v_L - q_{LC})$$

Mitigation in the L country due to the L country's own mitigation policy (under its "unconditional NDC policy") equals as noted v_L/γ; while additional mitigation due to the support payments from the H bloc equals q_{LC}/γ. R_{L0} is assumed to equal the "BAU" fuel consumption (and carbon emissions) with no carbon taxes, setting $v_L = q_{LC} = 0$ in (3.4).

The H country is assumed to not see which units of emissions reduction are implemented by the L country, and which are implemented by the H country's own support to L country mitigation. This leads to a problem of *missing additionality*: the H bloc must make support payments for all implemented emissions reductions beyond the BAU level, not just those that are additional due to the H country's support payments, but also those induced by the L country itself.

The H bloc's objective function can then be expressed as follows:

$$(3.5) \qquad V_{HC}(1) = v_H \frac{(1 - \rho)q_{LC}}{\gamma} - q_{LC}\frac{v_L + q_{LC}}{\gamma}.$$

v_H is as before the value of the carbon externality related to emission of one GHG unit, as valued by the H country. The first term in (3.5) is the gain for the H country from mitigation in the L country due to the MF support from the H bloc to the L country. This gain is partially eroded by positive "carbon leakage" at rate ρ. Carbon leakage reduces the effective rate of mitigation through

several possible mechanisms, both domestic and international.[12] With positive leakage, only a fraction $1-\rho < 1$ of the increased mitigation in the L country reduces global GHG emissions.

The second term is the H bloc's implementation cost, which includes payment for all mitigation implemented by both its own and the L country's NDC policy. Maximizing (3.5) with respect to q_{LC} yields

$$(3.6) \qquad\qquad q_{LC} = \frac{(1-\rho)v_H - v_L}{2} \ .$$

q_{LC} expresses the H country's WTP to support mitigation in the L country. Three factors lead to this level being set below v_H:[13]

1) *Missing additionality*, represented by the term v_L, representing mitigation implemented by the L country's government itself, that must also be paid for by the H country.

2) *Carbon leakage*. The term $(1-\rho)$ represents the fraction of the mitigation implemented by the H country's support which does not leak out.

3) *The factor "2"* in the denominator. This factor represents i) inefficiency facing the H country when paying a given fixed rate (q_{LC}) for all emissions reductions; and ii) the H country acting as a monopsonist reducing its payment below a competitive rate.[14]

Non-transformational project-based MF is included in this presentation mainly for comparative purposes to the (transformational) modalities to be discussed in sections 4-5. In section 2, this modality applies to the "low-level equilibrium" Q^* illustrated in Figure 1, where "low-hanging fruits" are harvested. This is a limited role; this modality has no role in our "transformational" analysis; and will likely play a very limited role under the PA going forward. It also has other limitations, among which we here mention two. First, its scope is limited as it applies only to relatively large free-standing projects (such as power plants and energy-intensive industrial units) and not to households or small businesses. Secondly, implementation costs can be high as costly

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[12] Rosendahl and Strand 2011 argue that the average leakage rate from the Clean Development Mechanism was about 30%; although it could be lower under the PA.

[13] An important fourth factor, not discussed here, is "baseline inflation" whereby the baseline against which future emissions reductions in L countries are judged can be inflated. For analysis see Strand 2011, 2016 and Kerr 2013.

[14] See Strand 2013 and Mundaca and Strand 2019 for more complete analysis.

methodologies often must be followed for verification of the GHG emissions reductions, and approval.

4. Transformational project-based MF

As widely recognized in recent literature, a radical contraction of fossil-fuel-intensive sectors, and a similar build-up of non-fossil energy use, at national, regional and global scales, will be essential for successful implementation of a transformational decarbonization program.[15] "Transformational project-based MF" represents a crucial component of such a transition. This was vividly illustrated in Figure 1, in section 2 above. As long as the $v_H e$ curve lies below the marginal cost (MC) curve for the donors (for Q below Q_C), the levelized cost of non-carbon energy investments is too high to make MF provision to support such investments in L countries beneficial to donors. As Q moves to the domain beyond the "tipping point" Q_C, however, supplying project-based MF becomes attractive for donors. Appendix 1 shows that the "tipping point" is reached whenever

$$(4.14) \qquad\qquad A < p + v_L + v_H,$$

where A is the levelized cost of establishing the new (non-carbon) energy technology. (4.14) is at the same time a basic condition on A for the transition to non-fossil technology to be efficient: (levelized) unit costs of the new technology ought to be less than the overall unit costs of the old technology, when climate cost components are included in the latter.

We may now relate this analysis to our broader discussion of "transformational climate finance" in section 2. The main relation is via the conditions for our solution here to be implemented; which relates to the relative position of the RMF (v_H times e; "marginal MF return") and MC ("marginal supply cost of MF funds") curves in Figure 1. When one is not yet in the "transformational" range for Q beyond Q_C, the RMF curve lies below the MC curve. The fundamental efficiency condition

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[15] See, among others, Fischer et. al. 2004; Rivers and Jaccard 2006; Kalkuhl et al. 2012; Lecuyer and Vogt-Schilb 2014; Audoly et al. 2014; Victor et al. 2019. World Bank 2016; Engle et al. 2018; Greaker et al. 2018; Vogt-Schilb et al. 2018; Rissman et al. 2020. See Popp 2019 for a survey of recent related work on low-carbon energy technology development. Audoly et al. 2014 calculate that net GHG emissions from the global electricity sector need to be reduced to (close to) zero by 2050 in order to reach the 2 degrees C global warming goal set as part of the PA. Full decarbonization will clearly be much more complex than discussed here. Rissman et. al. 2020 indicate paths to full decarbonization of key sectors by 2070, which require a combination of policy and MF support interventions similar to those discussed by us.

for a transformational switch to occur, (4.14), fails to hold when A is too high. H countries will then lack the incentive to provide the required additional MF.

When instead A is sufficiently low for (4.14) to hold, returns to MF supply for donors will exceed cost; more will be supplied; and Q_M^{**} will be a new stable (long-run) equilibrium for MF.

Our analysis does not detail the mechanisms by which the "transformational" phase for project-based MF supply can be reached; nor exactly how difficult it will be to reach. We here only identify some clues to how this development can be facilitated. When coordinated and targeted MF support is provided at a sufficiently large scale, its impact can be very large. Four key elements facilitate transformational project-based developments: i) high (global) R&D expenditure related to development of low-cost, low-carbon technologies; ii) high investments in low-carbon technologies and capital; iii) robust, comprehensive and sustained carbon taxation in L countries; and iv) high donor collaboration in raising MF funds for L countries. These factors all reduce the levelized investment cost in low-carbon (or non-fossil) technologies required to replace the existing fossil-based technologies; and lift the RMF curve in Figure 1.

5. Transformational policy-based MF: Implementing carbon taxation in L countries

This section discusses donor WTP to supply transformational policy-based MF to implement comprehensive and long-term predictable carbon taxation in an L country or country group. Our analysis is "economic" and devoid of political economy aspects. Influential recent work has shown that a development toward more massive mitigation-focused R&D and low-carbon investments will be stimulated by (high) carbon taxation, and be highly problematic without such taxation.[16] The receiving L country evaluates any policy in a simple way by its central government, and there are no roadblocks to implementation. We view this as a useful stage setting, to prepare for more realistic discussions where such constraints need to be observed.

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[16] Acemoglu et al. 2012, 2016; and Aghion et al. 2014, 2016; Gerlach, Kverndokk and Rosendahll 2014; see also Popp 2002, Gerlagh 2008, Hassler et. al. 2012, Golosov et al. 2014, Cramton et al. 2017, and Fried 2018. Andersson 2019 finds that a carbon tax is substantially more effective for inducing GHG mitigation, than a regular fuel tax of same magnitude. Tvinnereim and Mehling (2018) conclude that for "deep decarbonization" to take place, carbon pricing is necessary but not sufficient: it needs to be accompanied by other policy measures which include heavy support to non-carbon energy technology development and non-carbon energy projects.

We assume the same basic economic structure for the L country as in section 3, so that (3.1) - (3.2) still hold, but there is now no project finance. Assume that the H bloc offers the L country the option to set a uniform carbon tax, t, on top of its own carbon tax v_L from (3.2) to address its co-benefits of climate policy. We will study which level of t the H bloc will propose for the L country, and the mechanism(s) for incentivizing this tax.

The case considered involves *policy conditionality*: The H bloc provides a payment to the L country for the ("deadweight") periodic welfare loss from a carbon tax t, *conditional on the L country implementing this tax*, on top of its own carbon tax v_L. This compensation for deadweight loss will go forward whenever the carbon tax is in force in the L country. We focus on a case with no carbon leakage.[17]

Assume that each L country ignores the *climate* impacts of its emissions when determining its own climate policy, but takes into consideration the *non-climate* impacts of these policies on its own economy, as part of its "unconditional" NDC to the PA.

The level of uncompensated welfare for the L country when not supported by other countries is given by (3.1), and the L country's unconstrained optimal fossil-fuel consumption level R_L from (3.2). The welfare level for the L country before imposing a carbon tax (apart from its own co-benefits-motivated tax v_L) is

(5.1)
$$W_L* = \frac{(1-p-v_L)^2}{2\gamma}.$$

Call the carbon tax proposed by the H bloc t, considered exogenous to all economic actors in the L country, both private and public. Given that such a comprehensive carbon tax needs to be imposed, the L country determines R_L by maximizing its preference (welfare) function

(5.2)
$$W_L(p) = R_L - \frac{1}{2}\gamma R_L^2 - (p+v_L+t)R_L,$$

with respect to R_L which yields

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[17] A positive leakage case is considered in Appendix 2, which also discusses a case without policy conditionality but where the L country is given a compensation equal to the carbon tax supported by the H country. This is a less efficient scheme, and leads to a lower carbon tax being supported by the H country.

$$(5.3) \qquad R_{Lt} = \frac{1-p}{\gamma} - \frac{v_L}{\gamma} - \frac{t}{\gamma}.$$

Inserting from (5.3) into (5.2) yields the L country's welfare in this case:

$$(5.4) \qquad W_L = \frac{(1-p-v_L)^2}{2\gamma} - \frac{t^2}{2\gamma},$$

From (5.4), the L country experiences a welfare loss from imposing a comprehensive carbon tax t, equal to $t^2/2\gamma$. This corresponds to a so-called Harberger triangle, the "deadweight loss" to the economy from imposing the tax (Hines 1999). This is the minimum compensation that the L country must receive from the H bloc, to be willing to implement and maintain this carbon tax. Assume that the H bloc provides this level of compensation to the L country. We want to derive the optimal level of this carbon tax, from the point of view of the H bloc, given that the L country must be compensated in this way. The amount of mitigation induced by this tax is as noted t/γ (from (5.3)). The H bloc's net utility gain from this solution, relative to no carbon taxation, is then (where the first term is the value of the induced mitigation, while the second term is the required payment to the L country):

$$(5.5) \qquad V_H = v_H \frac{t}{\gamma} - \frac{t^2}{2\gamma}.$$

Maximizing (5.5) with respect to t yields:

$$(5.6) \qquad \frac{dV_H}{dt} = \frac{v_H}{\gamma} - \frac{t}{\gamma} = 0 \Leftrightarrow t = v_H.$$

From (5.6), the optimal carbon tax set by the H bloc to be imposed on the L country equals v_H, the per-unit carbon externality for the H bloc. The L country is assumed to impose its own carbon tax of v_L, so that the total (also optimal) level of carbon taxation in the L country is $v_L + v_H$.

The net welfare gain to the H country from imposing a carbon tax v_H on the L country, when the L country is exactly compensated for its welfare loss, is

$$(5.7) \qquad V_H* = \frac{v_H^2}{\gamma} - \frac{v_H^2}{2\gamma} = \frac{v_H^2}{2\gamma}.$$

The cost to the H bloc per unit of induced mitigation in the L country is

$$(5.8) \qquad c_H = \frac{v_H^2}{2\gamma} \frac{\gamma}{v_H} = \frac{v_H}{2},$$

or the same as the L country's welfare loss from implementing the carbon tax v_H, from (5.4). The return to the H country from this policy is then twice its cost of implementing it.

Aggregate surplus for the two countries (when the H country surplus is defined relative to the no-tax solution) is, based on (5.1) and (5.3):

$$(5.9) \qquad S = \frac{(1-p-v_L)^2}{2\gamma} + \frac{v_H^2}{2\gamma}$$

(5.9) gives the maximum welfare level improvement for country H, and (3.1) the minimum (benchmark) welfare level for country L. Country H needs to support country L by V_H^* from (5.7) per period as long as the carbon tax is in force. This compensation could be provided in various forms. It could be paid out at a level $v_H/2$ per unit of induced mitigation, v_H/γ, due to a carbon tax v_H. What is essential is *the basic policy conditionality involved*, namely to require that the L country imposes and permanently retains a carbon tax v_H on top of its own (co-benefits motivated) tax v_L, and compensates the L country directly for its utility loss related to this policy choice.

Three important impacts of comprehensive carbon taxation will be stressed.

First, transformational policy-based MF support to implement comprehensive carbon taxation is always efficient for both donor and receiving countries. By contrast, "transformational project-based MF" is efficient for the H country only when the transformational phase has already been reached (or one is "very close" to reaching it). Induced low-carbon technological change, when highly supported by public subsidies, lowers the cost of introducing a carbon tax, and increases the returns to it; see Gerlagh 2008, Fried 2018, and Liu and Yamagami 2018.

Secondly, carbon taxation lifts the v_H e curve in Figure 1, making the transformational range for MF easier to reach. This happens as the e function is shifted up: more mitigation is induced and more positive synergies released, in particular as private sector engagement in non-fossil energy development and production is stimulated.

Thirdly, comprehensive and robust carbon taxation has the potential to raise large fiscal revenues for L countries. This can be crucial for many of these countries whose ability to tax is highly constrained. Carbon taxes enable higher general-purpose and sorely needed fiscal expenditures, and may spur these countries' willingness to support non-carbon investments at home. The distributional impacts of L countries' carbon taxation is usually favorable as high-income households tend to have relatively high fossil-fuel consumption expenditures.

6. Collaborative action among donors to supply MF

6.1 Preliminary analysis

We have so far said little about the key parameter v_H, which defines the basic value to donors per unit of global GHG emissions reduction. For a non-altruistic donor, v_H depends on the expected climate impact of increased emissions as valued by that donor. This value will depend on geographical factors such as the H country's size and vulnerability to climate change. v_H will be greater when defined by a group of countries instead of by a single country.

Secondly, we have said little about how MF is actually collected and spent. A WTP to supply MF does not automatically lead to the funds being raised and paid out for their purpose, in the amounts predicted by our models.

We will now consider coordination of MF supply among donors, and mechanisms for raising the required funds. This is important when trying to understand both the WTP among H countries to provide MF, and the amounts of MF raised.

In a seminal related analysis, Bradford 2004 proposed an international institution, called the "International Bank for Emissions Allowance Acquisitions" (IBEAA), to raise voluntary MF contributions from donor countries, for *purchasing and retiring* GHG emissions reductions allowances in all (H, and L) countries, below "business-as-usual" (BAU) emissions.[18] While Bradford viewed the contributions to the IBEAA as exogenous, and did little to explain how to mobilize H countries' MF contributions, the determination of such contributions, and donors' implied valuation of GHG mitigation (their WTP), are key issues in this section. The discussion related to mobilizing MF focusing on roles of international funds or International Financial

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[18] David Bradford died tragically in a fire in his house in Princeton, N.J., in January 2005. His original ideas about mitigation policy were, unfortunately, largely forgotten upon his death.

Institutions (IFIs) has however to date been limited, and only limited MF has been mobilized. This section considers, at a relatively abstract level, the potential for such institutions to play a major and constructive role for such mobilization.

While the problem of combatting climate change has been called "the greatest market failure facing mankind" (Stern 2006), we in this section propose a mechanism with promise to deal with parts of this problem.[19] Most of the literature on this topic to date has attempted to derive rules for cooperative mitigation actions taken by individual countries, and has yielded implementable mitigation solutions which are far from globally optimal.

Our solution outlined here and in Appendix 3 differs fundamentally from most other proposals by focusing on far more direct control of individual contributions by participating countries.[20] The basic potential for individuals, institutions and countries to cooperate is widely recognized (Ostrom 1990, 2000). Much of the literature on cooperation for climate mitigation action stresses two central issues, captured here but largely absent from other proposed climate policy architectures: 1) a central institution for coordinating climate action; and 2) high visibility of climate policy targets and whether or not they are achieved by parties.[21] A centralized institution organizes and collects financial contributions for mitigation action, which is widely published, and easily observable. This makes it relatively easy to design effective reaction ("punishment") mechanisms for agreement enforcement. As also widely recognized (Fehr and Gächter 2000), deviations from a cooperative agreement will be punished by other players, often even when punishers do not gain from their punishment; in our case the punishing reactions are beneficial to punishers. Our assumed reactive strategies, of a "tit-for-tat" form, are highly plausible and realistic.

We assume that an IFI coordinates donor MF contributions, and study the impacts of such coordination on donors' WTP to supply MF to L countries. To simplify the presentation, we

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[19] For broader analyses see e g Stern et al. 2006; IPCC 2014 chapter 13; Barrett 2003, 2007; Nordhaus 2008; Victor 2011; and Hovi et al. 2015; for important recent analytical work see Finus 2001; 2008; Asheim et al. 2006; Bosetti et al. 2008; Nagashima et al. 2009; Fuentes-Alberto and Rubio 2010; Harstad 2016; Battaglini and Harstad 2016; Gersbach et al. 2017; and Ansink et al. 2018.

[20] Our presentation of analytical results in this section is based largely on Mundaca and Strand 2020.

[21] See Carattini et al. 2019. Dannenberg and Gallier 2019 argue that high individual (country) contributions requires the choice of coordinating institution to be endogenous, thus chosen by the participating countries in our case. Experimental results by Tavoni et al. 2011 indicate that high levels of inequality between participating parties reduces the likelihood of successful outcomes, but that better communication increases success dramatically, and promotes the amounts of transfers, here between H and L countries, in similar coordination games.

assume that one unit of MF provided through an IFI has given and constant efficiency in inducing GHG mitigation.[22]

Consider n identical H countries which may provide individual MF contributions, or coordinate them through an IFI. Denote the MF contribution of donor country i by Q_i, where one contribution unit allows for a reduction of GHG emissions in an L country by e units (where e, as before, indicates the efficiency of MF for global GHG emissions reduction through mitigation in the L country). As before, the value ascribed by each H country i to one unit of GHG mitigation is v_H. The net welfare to country i from providing an MF level of Q_i is (similar to (2.1))[23]

$$(6.1) \qquad W_{ic} = v_H e(Q_{-i} + Q_i) - (Q_i + \frac{1}{2}\sigma Q_i^2) .$$

$Q_{-i} = (n\text{-}1)Q_i$ is considered as exogenous by country i (assuming that all countries provide the same contribution). We assume e to be constant; and $v_H e > 1$ (a condition for positive MF).

Maximizing (6.1) with respect to Q_i yields the following *non-cooperative* solution Q_0 for Q_i:

$$(6.2) \qquad Q_0 = \frac{v_H e - 1}{\sigma} .$$

The optimal *cooperative* Q_i level for each contributing country is found by maximizing (6.1) with respect to Q_i, replacing $Q_{-i} + Q_i$ by nQ_i, which yields

$$(6.5) \qquad Q_i(opt) = \frac{n v_H e - 1}{\sigma} ,$$

which is more than n times its level from (6.2).

We will now consider possible equilibria to a repeated game between the n H countries, and an IFI which coordinates the countries' contributions. We will ask whether the fully cooperative solution,

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[22] In reality, individual donors may have more specific preferences concerning the disbursements of their MF contributions, including what types of projects and expenditures in L countries they desire to support. Such factors may impact on donors' willingness to supply MF, and may also affect the overall efficiency of such contributions. See e g Schneider and Tobin 2013 for discussion of such issues, and the impacts of coalition formation, in a European context.

[23] The reader may note that this parallel with section 2 does not hold perfectly. In section 2, Q could be interpreted also as a measure of accumulated MF, possibly together with current MF expenditures. To avoid over-burdening the presentation we choose to use the same notation for MF expenditures in both sections.

(6.5), can constitute an equilibrium for the participating H countries. To find such solutions, we need to study how much country i loses or gains by reducing its contribution marginally below the commonly agreed level Q_l.

6.2 Immediate reactions

We first assume that if one country reduces its initially agreed-on contribution level, "many" or all other countries also *immediately* do the same, in a "*tit-for-tat*" fashion (as a simple "*quid pro quo*"); and that the reaction lasts for the length of the deviation period. This requires individual contributions to be immediately observable by all n countries.[24] Thus, if country 1 deviates for one single period, other countries react to this deviation for the same period. Equivalent reaction strategy profiles have been applied in related climate-policy models by Barrett (1999) and Asheim et al (2006). The resulting MF contribution Q_l can be shown to be *renegotiation proof* (Farrell and Maskin 1989): All parties of the game can revert to the initial (cooperative) equilibrium after one period of deviation, which they may have incentive to do.

When country 1 reduces its climate finance contribution marginally, starting from the initial value Q_l, this triggers the same reductions from a positive share α (≤ 1) of the n-1 other countries.[25] We find, in Appendix 3, that the highest value of Q_l that corresponds to an equilibrium (and deters country 1 from deviating) is

$$(6.8) \qquad Q_{M1} = \frac{(1+\alpha(n-1))v_H e - 1}{\sigma}.$$

We see that when $\alpha = 1$ (all other countries react immediately to country 1's deviation), $Q_{M1} = Q(opt)$ from (6.5). This means that the fully cooperative solution is implementable as an equilibrium to the contribution game. When α is smaller, the "best" implementable cooperative Q level is lower than $Q(opt)$, and more so the smaller α is. Note also that, for any α, any Q level between (6.2) (the non-cooperative solution) and (6.8) (the best implementable cooperative solution) constitutes an equilibrium to this game.

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[24] In the next subsection we will assume that punishments need to be implemented with a one-period lag.

[25] We ignore integer constraints and treat n as continuous, without much loss of generality.

6.3 Delayed reactions

Consider a simple alternative where the responses of other H countries are delayed by a single period, with a constant discount factor δ between periods 0 and 1.[26] In other respects, the game has the same structure as with immediate reactions. We then show in Appendix 3 that the best implementable cooperative solution implies

$$(6.10) \qquad\qquad Q_{D1} = \frac{(1+\delta\alpha(n-1))v_H e - 1}{\sigma}.$$

Discounting reduces the highest Q level by each donor country that can be sustained as an equilibrium solution to this game.[27] This is due to the weakening of the reactions by other countries to a deviation by one H country, as it is not possible to react immediately but only after a lag. This reduces the severity of the punishment, and the group's ability to enforce particularly efficient equilibria, with high (close to optimal) RF levels from all donors.

6.4 Final comments

A conclusion from this section is that when several donors agree to provide MF funding, and one country's deviation from the agreement (by providing a smaller contribution than promised) is retaliated by the same reductions from other donors, "high" contribution levels from all donors constitute equilibrium solutions to this game. In a special case (*immediate* reactions from *all* other donors), even a fully cooperative solution is an equilibrium outcome. When reactions are not immediate, and/or not all other participating donors react to individual donors' deviations, the best implementable solutions are not fully efficient but can be close to efficient; and far superior to the non-cooperative solution.[28]

Our results imply that donor collaboration organized in this way can significantly increase donors' MF support to L countries, beyond donors' non-coordinated support levels. This analysis and result tie in closely with section 2, on how to reach the "transformational" phase for MF. Collaboration

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[26] δ can be taken to represent a combination of a regular discount factor and a probability that the game ends after any given period.

[27] The length of the reaction period can here be interpreted in terms of the discount factor δ: the lower this factor is, the longer the reaction period.

[28] The same basic features regarding scope for donor collaboration are also present when a subset of donors have formed a "climate club" with internal collaboration; the same enforcement mechanisms work for the club versus other donors.

among donors will lift the "return curve" for donors in Figure 1, $v_H e$, to a higher level, by increasing the donor value attached to mitigation activity, from v_H in the non-cooperative case, to a level closer to nv_H (the mitigation value ascribed to individual donors under full and efficient cooperation). This makes the transformational range for MF (perhaps much) easier to reach.

Adding to these arguments, and discussed further in Appendix 3, donors' cooperation can further enhance the efficiency of their MF supply by making it conditional on GHG mitigation efforts by the L countries themselves.[29] Such conditionality is easier to demand and enforce when H countries cooperate in their MF supply.

7. Conclusions

This paper discusses mitigation finance (MF) provision from high-income (H) donor countries to lower-income (L) countries, focusing on H countries' "willingness to pay" (WTP) to provide such MF. In section 2, we study the conditions for reaching a "transformational" stage and range for MF; this requires moving past an initial range where returns to MF provision for H countries are lower than its costs to these countries. We consider three "modalities" for MF provision: "non-transformational project MF" ("traditional" individual-project support; in section 3); "transformational project MF" (to transform entire energy-intensive sectors from fossil-fuel-based to non-fossil-based energy inputs; section 4); and "transformational policy based MF" (comprehensive carbon tax implementation; section 5). The returns to transformational policy-based MF (carbon tax implementation) are particularly high for donors when the L country is compensated directly for the welfare loss of implementing a carbon tax and MF support from H countries is conditional on policy implementation. The returns to transformational project-based finance (applied to complete sectoral transformations in L countries) can also be high when unit costs of non-fossil energy investments have already been driven down to a low level through extensive global R&D efforts and local, regional and global learning effects. This case is in this paper developed only in a rudimentary way and requires development in follow-up work.

The return for donors to non-transformational MF is lower than for the transformational MF modes due to serious inefficiencies with the former. Non-transformational project MF also has less scope

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[29] See Mundaca 2020 for analysis of cooperation for mitigation action among receiving countries, a potentially important issue not included in this analysis.

for application, as it cannot usefully and practically be applied to many emissions sources (households; small businesses), and often requires complex methodologies for implementation.

Two features can be held out as particularly important for spurring the transition to the "transformational" MF domain as discussed in section 2.

First, robust and comprehensive carbon taxation in the L countries increases the "returns to MF" function e. Transformational project finance becomes much more potent when accompanied with high carbon taxation, in particular as private-sector engagement is then highly incentivized.

Secondly, collaboration between donors in supplying MF increases the value of mitigation to donors (v_H in Figure 1), as each donor then incorporates the mitigation preferences of other donors. We show in section 6 that cooperative MF contributions, far higher than those supplied non-cooperatively, can be sustained as equilibria in a multi-period game between donors and an implementing organization with simple "tit-for-tat" reaction strategies. Both factors serve to move the "returns curve" $v_H e$ in Figure 1 up. This eases and spurs the transition to the transformational Q range.

Our analysis and results feed into work to better understand whether "transformational" climate policy developments are feasible on a global scale when such developments require substantial climate finance contributions from high- to lower-income country groups. We consider our results as promising for gaining a better understanding of how such developments can be achieved, although gaps in the analysis remain. A key roadblock is to understand more fully how the crucial move from the current (non-transformational) state to "transformational" states can be explained and realized. Our paper does not formally account for how this transition actually takes place. Among other issues not sufficiently addressed, which need treatment in follow-up work, are how to incentivize private-sector climate finance, likely to provide most of the investment resources required for transformational developments; and how to overcome political economy barriers to transformational policy changes (carbon taxation); these have been major roadblocks to date.

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Appendix 1: Simple model illustrating "transformational project-based MF"

This appendix derives conditions for implementing a "transformational" project-based MF policy. Consider a broad investment program to replace the L countries' fossil-driven energy-intensive sectors with non-fossil energy. Global (levelized) costs related to investing in non-fossil energy capacity here need to be lower than global social and private costs related to continued operation of fossil-fuel generation plants (even when investments in the latter plants are already sunk and not subject to our cost accounting here). We assume that this condition holds; otherwise it is generally not efficient from a global perspective to phase in renewables. As shown by Gillingham and Stock (2018), this condition already holds for many technologies at today's stage of renewable energy development; and these costs are likely to keep falling. Consider a given levelized investment cost A per output unit per time period (which includes current costs of capital amortization and operation).

Assume that the donor can influence the L country's phase-in of renewable energy in its energy-intensive sector. All production units are assumed identical, and all can be replaced by identical-sized renewable-energy plants. This can justify a drastic solution where the entire "park" of fossil-fuel-fed plants is substituted with a "park" of plants supplied by non-fossil energies. When non-fossil energies have been phased in, the new power facilities are assumed to give rise to no negative externalities (such as local pollution), and no GHG emissions.

A complete substitution of non-fossil energy for fossil fuels is likely to require large initial investments. Such a replacement of utilities may convey large benefits to the L country, due to co-benefits (lower air pollution when the initial electricity generation was coal-based), low operating costs after investments have been sunk, and improved energy supply.

Climate finance support from H countries, to cover part of the investment costs, is considered as necessary to provide the correct incentives to the L country, and to secure the required additional outside financing.

Assume that the donor provides subsidies to the up-front investments, necessary for the projects to take off in the L country and receive the other international funding for their implementation. A minimally distortive subsidy takes the form of a (lump-sum) MF support S (per plant) to the L country, to cover part of the finance cost required for the non-fossil investment.

We will not discuss any further financing issues facing the respective L countries and their private sectors; only refer to the (preliminary) discussion in Strand 2019.

The energy-intensive sector in the L country initially relies on fossil fuels and comprises a fraction $1-h$ of the economy's total energy consumption. Otherwise, the two parts of the economy have the same basic analytical structure. This sector is represented by the following net utility function:

(4.1)
$$W_F(L) = R_F - \frac{1}{2(1-h)}\gamma R_F{}^2 - (p + v_L)R_F .$$

Here subscript F represents fossil fuel-based production in the energy-intensive sector. The optimal choice of energy use in the energy-intensive sector, by the L country government itself, is

(4.2)
$$\frac{dW_L}{dR_F} = 1 - \frac{\gamma}{1-h}R_F - (p+v_L) = 0 \Leftrightarrow R_F = (1-h)\frac{1-p-v_L}{\gamma}.$$

Welfare of the L country related to the initial (fossil fuel-based) production in the energy-intensive sector is then found by substituting from (4.2) into (4.1), yielding

(4.3)
$$W_F = (1-h)\frac{(1-p-v_L)^2}{2\gamma}.$$

Initial carbon emissions are given by

(4.4)
$$E_F = (1-h)\frac{1-p-v_L}{\gamma}.$$

The welfare loss for the H country, related to these initial fossil-based emissions, is

(4.5)
$$L_F(H) = (1-h)\frac{1-p-v_L}{\gamma}v_H.$$

The utility provided to the L country from this sector is

(4.6)
$$W_F(L) = (1-h)\frac{(1-p-v_L)^2}{2\gamma}.$$

The net welfare related to the fossil-based, energy-intensive sector in the L country is then

(4.7)
$$W_F = (1-h)\left[\frac{(1-p-v_L)^2}{2\gamma} - \frac{1-p-v_L}{\gamma}v_H\right] = (1-h)\frac{(1-p-v_L-v_H)^2 - v_H^2}{2\gamma}.$$

This sector is now replaced by a new non-fossil-based sector, with the same basic structure except that levelized investment costs per unit of output equals A. Annualized net utility (minus all investment costs that need to be covered) from this sector of the L country, when renewable energy plants are completely phased in, is then given by:

(4.8)
$$W_E = R_E - \frac{1}{2(1-h)}\gamma R_E^2 - AR_E.$$

(4.8) represents the new non-fossil energy-intensive sector in the L country, assumed for simplicity to have a very similar structure as the original, fossil-intensive, sector. The parameter A in (4.7) can be interpreted as the levelized (annualized) cost of non-fossil energy production when investing in and operating the most profitable renewable energy facility (or a group of such facilities).[30] The main difference between (4.6) and (4.1) lies, first, in different levelized total costs for all production units, with higher (lower) total costs for renewables when $A > (<) p$ (but where otherwise the distributions of costs across production units are identical). Secondly, with non-fossil

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[30] Note that perceived levelized per-unit costs may differ between H and L countries, with costs typically being higher for L countries, due to higher discount rates.

energy there is no climate externality (nor any externality expressing co-benefits for the L country). This leads to a "globally optimal" solution (as viewed jointly by the H and L countries) for R_E. This solution, denoted R_{EN}, is:

(4.9)
$$R_{EN} = \frac{1-h}{\gamma}(1-A).$$

The utility provided to the L country from this sector is found by inserting from (5.9) into (5.8), yielding

(4.10)
$$W_{EN} = (1-h)\frac{(1-A)^2}{2\gamma}.$$

We further assume:

(4.11)
$$A > p + v_L$$

so that transformational non-fossil energy investments are not profitable for the L country without investment subsidies. This makes $W_F(L)$ from (4.6) larger than W_{EN} from (4.10), which means that for the L country to adopt the new energy technology, it must receive a subsidy, which we call A_1, from the H country to implement the new technology. Consider this subsidy set so as to make the L country exactly indifferent between the new and the old technology. A_1 is given by:

(4.12)
$$A_1 = \frac{1-h}{2\gamma}\left[(1-p-v_L)^2 - (1-A)^2\right].$$

 Efficiency of the transition, which justifies the H country's subsidy A_1, also requires that the subsidy is no greater than the H country's gain from eliminating the GHG emissions from the initial fossil production, given by (4.5). Consider A_1 set at its lowest possible level, so as to make the L country exactly indifferent to accepting and not accepting the new technology. This gives rise to the following condition for the transition to be efficient:

(4.13)
$$(1-A)^2 \geq (1-p-v_L-v_H)^2 - v_H^2.$$

As long as the following condition holds:

(4.14)
$$A < p + v_L + v_H,$$

(4.13) will also hold. The welfare gain for the H country due to supporting the non-carbon transition in the L country (given that the L country is indifferent about the transition) is

(4.15)
$$G = \frac{1-h}{2\gamma}\left[(1-A)^2 - (1-p-v_L-v_H)^2 + v_H^2\right].$$

We here assume that (4.11) is fulfilled so that some MF contribution from the H country is required for the non-fossil transition. The gain per unit of finance provided is G divided by A_1. These are maximal values: When the L country itself has some gain from this transition, the gain to the H country will be smaller.

(4.14) is here the basic condition for efficiency of the transition to non-fossil technology to be efficient: overall (levelized) unit costs of the new technology can be no greater than (better, less than) the overall unit costs of the old technology, when the climate cost components are included in the latter. We see that (4.13) is slightly less strict than (4.14). This is due to the excessive emissions rate implied by the old technology to be phased out, which is due to the energy capacity of the old plants being too large due to lack of effective carbon taxation as basis for that scaling.

Appendix 2: Transformational policy-based MF

Case a: Positive leakage

Consider in section 5 the case with carbon leakage (to other countries) at rate ρ, related to a carbon tax being implemented in one L country. The amount of effective global mitigation induced by a given carbon tax t is then $(1-\rho)t/\gamma$. Inserted into (5.5) this yields

$$(5.9) \qquad V_H = v_H \frac{(1-\rho)t}{\gamma} - \frac{t^2}{2\gamma}.$$

Maximizing (5.9) with respect to t yields:

$$(5.10) \qquad \frac{dV_H}{dt} = \frac{(1-\rho)v_H}{\gamma} - \frac{t}{\gamma} = 0 \Leftrightarrow t = (1-\rho)v_H.$$

The WTP of the H country for each unit of mitigation induced in the L country is now reduced to $(1-\rho)v_H$, due to carbon leakage at rate ρ.

The cost for the H country, per unit of effective global mitigation (considering the lower impact on global emissions through leakage), is

$$(5.11) \qquad c_H = \frac{t^2}{2\gamma} \frac{\gamma}{(1-\rho)t} = \frac{t}{2(1-\rho)} = \frac{v_H}{2}.$$

Leakage leads to a lower preferred carbon tax by the H bloc in the L country. But it at the same time leads to a lower reduction of GHG emissions in the L country related to implementing this carbon tax. This reduces the required compensation from the H bloc to the L country equivalently. The implementation cost per implemented mitigation unit then stays at the same level as with no leakage, from (5.8).

What does this mean for the WTP of H countries to provide MF to L countries? Their WTP per unit of induced mitigation (net of carbon leakage) is still v_H. We can also ask a related question: How much mitigation is one unit of payment, equal to the H country's value per unit of additional global mitigation, v_H, able to buy? The return to H countries from such a payment is still 2 units of mitigation (reductions in GHG emissions) per unit of MF made available to L countries.

Case b: Fixed unit support payment

An alternative way for the H country to support carbon tax implementation in the L country is to provide direct support to the L country for each unit of GHG emissions reduced by a carbon tax. The H country in this case no longer imposes a policy conditionality condition (as it did in section 5) and instead demands the L country to charge a carbon tax, s, and support this tax with the same

subsidy rate per unit of mitigation provided by, and set by, the H country. The total support payment provided by the H country is then s^2/γ, as the implemented mitigation from this tax will be s/γ. The net utility for the H country from such a policy is

(5.12)
$$V_{Hs} = v_H \frac{s}{\gamma} - \frac{s^2}{\gamma}.$$

Maximizing (5.12) with respect to s yields:

(5.13)
$$\frac{dV_{Hs}}{dt} = \frac{v_H}{\gamma} - \frac{2s}{\gamma} = 0 \Leftrightarrow s = \frac{v_H}{2}.$$

The optimal tax support per mitigation unit from the H to the L country in this case equals half of the H country's value per unit of mitigation, v_H. It is natural to define this s level as the donor's "WTP to support mitigation in the L country" in this case, although the value to the H country of one unit of GHG mitigation in the L country is still v_H. This is parallel to result (3.6) in section 3, with non-transformational project MF (for a donor behaving monopsonistically), where the donor is deterred from paying a higher support price as the H country limits L country mitigation to extract rents through "low" project support prices. The policy conditionality solution in sub-section 5.1 (with direct compensation for the L country's deadweight loss) is clearly more efficient than the "full mitigation support" solution considered here.

Appendix 3: Further analysis of cooperative solutions, section 6

Consider, in section 6, n identical H countries which may either contribute MF individually, or coordinate their MF contributions through a fund or international financial institution (IFI). Denote the MF contribution of donor country i by Q_i, where one contribution unit allows for a reduction of GHG emissions in the respective L country by e units (where e indicates the efficiency of MF as applied for global GHG emissions reduction through mitigation in the L country). As before, the value ascribed by each individual H country i to one unit of GHG mitigation is v_H. The net welfare to this country from providing an (non-coordinated) MF level of Q_i is assumed to be given by

(6.1)
$$W_i = v_H e Q_i - (Q_i + \frac{1}{2}\sigma Q_i^2).$$

(6.1) takes the same basic form as (3.1) in section 3, where the expression in parentheses represents the cost to the country of providing MF. As before, the donor's marginal WTP to supply MF is falling in the amount of MF supplied (as the political will to supply MF is likely to be limited). $v_H e > 1$ is a condition for the MF contribution to be positive.

Maximizing (6.1) with respect to Q_i yields the following non-cooperative solution Q_0 for Q:

(6.2)
$$Q_0 = \frac{v_H e - 1}{\sigma}.$$

Assume that n donor countries contribute to a coordinating fund for the purpose of mitigating GHGs in L countries. We still assume that the amount of GHG mitigation executed is proportional to the amount of funding provided to these countries through the fund.

We will study equilibrium MF contribution levels by the *n* H countries. We start from an agreed-upon solution, and check whether this solution can constitute a long-run equilibrium for each of the *n* H countries. In this solution each H country is assumed to contribute the same amount $Q_1 > Q_0$ (to the coordinating fund) for this purpose. Assume that all *n* countries have agreed that each will contribute this amount per time unit (year or multi-year period), but, no higher or lower level.[31] The agreement is conditional on each country not reducing this level Q_1. The total amount of MF for implementation of GHG mitigation in L countries by the coordinating fund is then assumed to be nQ_1. If one country increases its own contribution beyond Q_1, no other country follows suit but retains its initial contribution Q_1. We will not explain how a solution with all H countries contributing Q_1 was initially established.

The net benefit or utility (per-period, potentially for an indefinite number of periods) from participating in such a cooperative solution, with a given annual MF contribution to the coordinating fund, can be expressed, from the point of view of country *i*, by the following relation:

$$(6.3) \qquad W_{ic} = v_H e (Q_{-i} + Q_i) - (Q_i + \frac{1}{2} \sigma Q_i^2)$$

where $Q_{-i} = (n-1)Q_i$ is considered as exogenous by country *i*. We view *e* as constant; in reality *e* may vary with total MF supplied, as in the previous section.

We first consider what would constitute a best ("optimal") level of Q_i from the point of view of each H country *i*, when all Q_i are set at identical levels (which also will be optimal, as any optimal contribution solution will be symmetric). With identical Q_1 levels,

$$(6.4) \qquad W_{ic} = v_H e n Q_i - Q_i - \frac{1}{2} \sigma Q_i^2 .$$

Maximizing (6.4) with respect to (negative changes in) Q_i yields

$$(6.5) \qquad Q_i(opt) = \frac{n v_H e - 1}{\sigma} .$$

Optimal aggregate MF from all H countries is then (multiplying by *n*)

$$(6.6) \qquad Q_{TOT}(opt) = \frac{n^2 v_H e - n}{\sigma} .$$

The optimal cooperative contribution increases rapidly in *n*. There is then also a very large potential gain from cooperation, both in terms of the optimal MF contributions, and the utility to H countries from these contributions.

Note finally that (6.5) is optimal only from the point of view of H countries, and not L countries. Climate impacts will be adverse also for L countries as a group. This implies that the globally optimal mitigation effort is then (perhaps much) greater than (6.5).

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[31] We do not bar any participating country from contributing more MF than this level; such excessive contributions will however be fully voluntary and not have any impact on other aspects of this example.

Immediate single-period reactions

We will now derive cooperative solutions that form equilibria in a repeated game between the n H countries, with relatively simple and intuitive dynamic strategies. We ask whether the fully cooperative solution, (6.5), can constitute an equilibrium for the participating H countries. To answer this question, we need to study how much country i loses or gains by reducing its contribution marginally below the commonly agreed level Q_1.

A crucial aspect is the reactions of other countries to a (negative) deviation from the established solution by any one of the n H countries, when that country's MF contribution is set below Q_1. We now assume that if one country deviates by reducing its agreed-on contribution level, "many" or all of the other countries *immediately* do the same in a "*tit-for-tat*" manner (alternatively, as a simple "*quid pro quo*"). Such reactions require that the contribution from a given country is immediately observable by all n countries.[32] However, we assume that the reaction lasts for only the length of the deviation period. Thus, if country 1 deviates for one single period, other countries also react to this deviation for (and in) only this single period. An equivalent reaction ("punishment") strategy profile has been applied in previous related models by Barrett 1999 and Asheim et. al. 2006. An important feature of this reactive strategy is that the resulting equilibrium MF contribution Q_1 is *renegotiation proof* (Farrell and Maskin 1989; Benoit and Krishna 1993): All parties of the game are able to revert to the initial (cooperative) equilibrium after having deviated for one period, which they generally have incentives to do.

When country i now reduces its climate finance contribution marginally, starting from the initial value Q_1, this will trigger the same reductions from a positive share α (≤ 1) of the n-1 other countries.[33] Consider $\alpha < 1$, so that some countries do not immediately reduce their contributions. This leads to less effective enforcement. The utility change for country i in response to a small reduction in Q_i can be represented as

(6.7)
$$\frac{dW_{ic}}{-dQ_i} = -(v_H e(1+\alpha(n-1))+1+\sigma Q_1.$$

Consider an initial Q_1 which makes country i indifferent about reducing or retaining its MF level. To find this level, we find the solution for Q_1 that gives equality to zero in (6.7):

(6.8)
$$Q_{M1} = \frac{(1+\alpha(n-1))v_H e - 1}{\sigma}.$$

A larger Q_1 here gives greater incentive for country i to deviate from the cooperative solution by marginally reducing its contribution below Q_1. It follows from the last term σQ_1 in (6.7): the larger Q_1, the larger is the expression on the right-hand side in (6.7). This makes this expression positive (providing incentives for deviation by making a smaller contribution) when Q_1 is large; and negative (deterring a reduced contribution) when it is small. It is then also clear that when country i has incentives to retain its contribution at Q_1, it does not have incentives to reduce its contribution starting from a lower contribution level than Q_1.

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[32] In the next subsection we will assume that punishments need to be implemented with a one-period lag.
[33] We here ignore integer issues and treat n as a continuous variable, without much loss of generality.

If $Q_I = Q_{MI}$, country i is indifferent about retaining this level or reducing it slightly. Country i then retains its initial level of Q_I given that $Q_I \leq Q_{MI}$, and otherwise reduces it. Condition (6.8) is then sufficient for country i to never deviate from the established cooperative equilibrium, given that $Q_I \leq Q_{MI}$.

A larger α gives a larger upper bound on the range of possible equilibria for Q_I. When $\alpha = 1$ (all countries retaliate immediately), the optimal solution (6.5) for the n H countries can be implemented as a stable contribution equilibrium, as (6.8) and (6.5) coincide in this case.

There is here not symmetry with respect to increases and decreases in Q, starting from an initial level of Q between (6.2) and (6.8). We thus rule out that an *increase* in Q_i by one country can be followed by similar *increases* by other countries.

Delayed reactions

Consider a simple alternative where the responses of other H countries are delayed by a single period, with a constant discount factor δ between periods 0 and 1. (δ can be taken to represent a combination of a regular discount factor and a constant probability that the game ends after any given period.) Assume, as before, that one country deviates from an established equilibrium path for contributions to the fund, by a small reduction in its current-period contribution only; and that a share α of other H countries reacts by reducing their contributions by equally much, but now in the *next* period, thus with a one-period time lag. This is still a "*tit-for-tat*" reaction strategy, but with delayed punishment relative to the deviation by country i. To keep the analysis simple (and parallel to the previous section), we assume that the deviating country i reverts to the initial equilibrium level of Q from the next period on (thus, in the period when other countries are retaliating). This implies that we can focus on only two periods: the current "deviation period", when country i deviates from the agreed solution, and the following "punishment period" when other countries retaliate against this deviation. (We could otherwise in principle consider a case where the game is repeated perhaps infinitely with no end period, and the new and lower Q levels are retained. As long as the "*tit-for-tat*" punishment structure is retained, an extension to multiple or infinite periods will not fundamentally change the solution.)

The expression corresponding to (6.7) now takes the form:

(6.9)
$$\frac{dW_{ic}}{-dQ_i} = -(v_H e(1 + \delta\alpha(n-1)) + 1 + \sigma Q_1.$$

Consider the initial level of Q_I which makes country i indifferent about reducing and not reducing its mitigation level in the initial period. We then need to find the solution for Q_I that gives equality to zero in (6.9), which is

(6.10)
$$Q_{D1} = \frac{(1 + \delta\alpha(n-1))v_H e - 1}{\sigma}.$$

Discounting reduces the maximal Q level by each donor country sustained as an equilibrium solution to this game, when compared to the immediate punishment case. This follows from the weakening of the reactions by other countries to a deviation by one H country, as it is not possible to react immediately but only after a lag. The positive discount factor then reduces the value of the punishment from the point of view of any country i.

Whenever the initial Q_{i1} lies between Q_0 from (6.2), and Q_{D1} from (6.10), such solutions constitute stable equilibria in the sense that no participating country has incentive to reduce its contribution (but neither to increase it), starting from these initial contribution levels. This holds for all countries, as the solution is symmetric.

Implications of donor cooperation for L countries' own GHG mitigation activity

While the solution characterized by (6.5)-(6.6) is "optimal" from the point of view of participating donors, it is not globally optimal, as L countries' collective preferences for GHG mitigation are not being considered. The optimal global mitigation effort, and MF supply, are therefore larger.

We have so far in this section focused on MF mobilization among H countries and said nothing about how mitigation activity by L countries themselves can be stimulated by increased MF. Conditionality schemes, making increases in donors' MF supply dependent on higher mitigation effort by L countries themselves, can move the collective MF effort closer to the global optimum. An important factor is the potential for policy conditionality when donor countries cooperate. Such cooperation among donors could be extended also to effective cooperation between H and L countries, thus expanding cooperation to an even much wider set of countries.

We will not go into a deep technical discussion of such issues here, only make a few observations.[34] Clearly, L countries benefit from the higher level of MF funding that results from this type of donor cooperation; even when the direct impact on climate change related to their own GHG emissions is small for most of these countries. One reason is co-benefits from such additional mitigation efforts as stressed earlier (through lower air pollution, lower congestion and other externalities in road traffic, better energy security, etc.). Another is long-run impacts of new energy capital, which reduces variable energy costs, and increases total energy supply. L countries will then themselves have various benefits from such increased MF supply. Efficiently designed conditionality schemes, whereby increased MF supply from H countries is made conditional on L countries' mitigation efforts beyond their "minimum" levels (defined by their unconditional NDCs for fulfilling the PA), would further increase L countries' mitigation, and/or lower the costs to donors of implementing given mitigation programs. Such increases in L countries' own mitigation efforts could also lead to further positive feedbacks on H countries' own MF supply; such impacts are demonstrated in Mundaca and Strand 2020.

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[34] See Mundaca and Strand 2020 for further analytical discussion.

List of acronyms/abbreviations used in the paper

BAU = business-as-usual

GHG = greenhouse gas

H country = high-income/donor country

IBEAA = International Bank for Emissions Allowance Acquisitions

IFI = International financial institution

IPCC= Inter-Governmental Panel on Climate Change

L country = low-income (Bank client) country

MC = marginal cost

MF = mitigation finance

NDC = nationally determined contribution (to the Paris Agreement)

PA = Paris Agreement

R&D = research and development

RBCF = results-based climate finance

RMF = returns to mitigation finance

WTP = willingness to pay