ALIGNING CARBON MARKETS WITH NET-ZERO EMISSION TARGETS AND THE ROLE OF RESULTS-BASED CLIMATE FINANCE

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Abstract

This paper discusses whether the Article 6 carbon market mechanisms under the Paris Agreement (PA) can be expected to promote a development for global greenhouse gas (GHG) mitigation that will lead to a net-zero GHG emissions (NZE) solution by 2050 or somewhat later. We discuss factors which make such a development difficult or less likely. One factor is that the PA does not allow for banking of internationally traded mitigation outcomes (ITMOs) between PA trading periods. This is likely to lead to a lower ITMO price than otherwise in the first PA implementation period (up to 2030), putting a brake on GHG mitigation and delaying the NZE transition. The NZE process can also be delayed by a low early ITMO price spurring the transition to "intermediate" mitigation solutions, which can later serve as roadblocks to the transformative solutions required to reach the NZE. A third issue is that private-sector costs of renewable energy investments in most emerging markets and developing economies (EMDEs) are higher than globally optimal. This puts another brake on transformative energy investments, most so when the carbon price is low. Substantial dedicated climate finance from donors may be required, as up-front investment support, and as results-based climate finance (RBCF), to support the implementation of carbon taxation in EMDEs, to incentivize the net-zero transition in EMDEs which represent the bulk of GHG emissions during the transition phase to the NZE. We analyze how this transition can be speeded up by donor provision of RBCF to EMDEs as reward for implementing comprehensive carbon taxes. We finally model certain aspects of a global NZE given that this solution can be reached by 2050 or somewhat later. This solution requires wide application of negative emissions technologies (NETs), and requires some countries (typically, those with high income) to take on net negative emissions levels and targets, using NETs.

1. Introduction

The world has embarked on solving a task of a dimension never before attempted: to eliminate its total net emissions of global greenhouse gases (GHGs) by 2050 or slightly later. This task implies several partial but big sub-tasks. One is to virtually replace the largely fossil-fuel based energy supply with an alternative energy supply structure. GHG emissions also need be virtually eliminated from its other sources including deforestation, agriculture, waste and industrial processes. Secondly, negative emissions technologies (NETs) need to deployed to counter any remaining GHGs.

The most demanding of these tasks is to drastically reduce the importance of fossil fuels in the global energy supply, and replace these fuels with other energy sources. A leading authority on international energy markets, Daniel Yergin, comparing different global energy transitions that the world has faced over the last 300 years, asserts that[1]

"… this (task) is like no other. All previous transitions were driven largely by economic and technological advantages—not by policy, which is the primary driver this time. Each of the preceding transitions unfolded over a century or more, and none were the type of transition currently envisioned. The objective of this transition is not just to bring on new energy sources, but to entirely change the energy foundations of what today is a $100 trillion global economy—and do so in little more than a quarter century. It is a very big ambition, nothing on this scale has ever been attempted up to now."

This target is difficult but not impossible to reach. It requires an unprecedented effort and focus by all parties, with no time nor resources to spare in putting up this effort.

Ambitious but realistic target setting represents a first element. Most countries have, by early 2023, defined and set two related long-term targets for reducing their greenhouse gas (GHG) emissions. The first is the long-term target defined under the Paris Agreement (PA), that the globally average temperature increase (since pre-industrial times) shall be kept to no more than 2 degrees Celsius, with a more ambitious, aspirational, goal of 1.5 degrees Celsius. The second is a set of targets for most major GHG-emitting regions, to achieve zero net carbon emissions by 2050 (the US, EU) or somewhat later (2060 for China, 2070 for India). A question is whether these two sets of targets

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[1] See Yergin 2022.

are compatible, and whether reaching net-zero by 2050 or somewhat later, and retaining zero GHG emissions from then on, are sufficient to reach the long-term PA climate goals.

Key questions to be answered in this paper are:

Can an international carbon market, as set up under Article 6 of the PA, be expected to deliver a net zero solution by around 2050?

If not, what are main obstacles to reaching such an outcome?

How can these obstacles best be addressed?

These questions will be related to a further set of targets, the Nationally Determined Contributions (NDCs) set by each party to the PA, with current targets set for 2030. The NDC targets are subject to updating making them gradually more (and never less) demanding over time. As widely agreed, the NDC targets are however not sufficiently restrictive for the world to be on a realistic path to reaching the 2 degrees Celsius long-run PA target; and even farther from the 1.5 degrees Celsius target, or a net-zero GHG emissions (NZE) solution, by 2050.

Two market mechanisms for ITMO trading, defined under Articles 6.2 (for bilateral trading) and 6.4 of the PA (a centralized trading mechanism), have the potential to dramatically reduce parties' net mitigation costs (relative to no trading), and also bring substantial net revenues to parties that can sell carbon credits, to be dominated by emerging markets and developing economies (EMDEs), and some of the lowest-income countries (LICs). See e. g. Piris-Cabezas et al. 2019, and Edmonds et al. 2021. The latter indicates that implementation costs of reaching the parties' 2030 targets can be reduced by up to $300 billion per year by using these trading mechanisms maximally and efficiently. If such cost savings are applied to increase parties' climate policy ambitions, the mitigation outcome of the PA can be improved dramatically already by 2030.

ITMO trading will occur between parties in over- and under-balance relative to their NDC targets, and serves to reduce parties' overall implementation costs. But it is far from certain that the ITMO markets will turn out to realize their full potential (see Strand 2022). Three classes of ITMO markets (spot markets, forward markets, and options markets) must be made available to maximize their attractiveness to parties, and allow parties to realize their potential market returns. Strand 2022 however argues that relevant put and call options markets, and even a late ITMO spot market (near 2030), may not exist unless substantially supported by donors via finance funding and back-up guarantees. Note that two large parties, the European Union and the United States, both of which are large potential net ITMO buyers, have (so far) expressed no intent to participate in the ITMO markets. This is also a factor that contributes to uncertainty about the ITMO markets' existence and viability, in particular on the buyer side. High uncertainty about the markets' viability, functioning and existence may lead parties to not rely on the ITMO markets for NDC compliance, but instead aim to reach their NDC targets much more on their own.

A main challenge for many parties will be to stay on course to reaching their own-proclaimed net-zero targets by 2050 or somewhat later, in particular if donor-supported climate finance turns out to be limited. For EMDEs and LICs, two sets of plans for major future GHG emissions reductions are realistic. First, parties need to fulfill their own unconditional NDC PA targets, largely through self-financed domestic mitigation. Donors can however provide some support to reach parties' NDC targets. An alternative way is to have their renewable energy investments partly or fully financed by outside resources.

The amount that can be incentivized beyond the unconditional NDC will be closely tied to the carbon price in the ITMO market facing the party, relative to the carbon price implied by the party's unconditional NDC target. If this price turns out to be relatively low (for low-income parties, in particular in the forward ITMO market in relatively early trading), only limited mitigation will be incentivized through ITMO market trading in the absence of outside financial support; and incentivized energy investments may turn out to be largely "non-transformational". This will hamper parties' abilities to remain on course to net-zero in the current PA implementation period up to 2030. As shown in section 2, PA implementation could then instead work against reaching an NZE, in the absence of heavy climate finance support from donors.

Three additional issues, focused on in sections 2-3, can make it difficult to reach the net-zero targets when relying on PA mechanisms. First, the carbon crediting mechanism under the PA faces problems as the Article 6 rules of the PA do not allow for banking of excess ITMO holdings from one (10-year) implementation period to the next. [2] This leads to a "chopping-up" of the entire PA implementation agenda, with a high possibility that ITMO trading prices will be low in large parts

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[2] The choice of future 10-year target periods under the PA are not yet set in stone; this will be clarified over the next five years.

of the first period (up to 2030), and possibly also in later periods if rule changes are not implemented.

A problem may then arise when there is overshooting of NDC targets by several parties. The global mitigation level could then have the possibility to proceed more rapidly, and the net-zero target reached sooner. The lack of banking will however hamper this process. It can lead to (close-to) zero ITMO prices and a depressed incentive to mitigate beyond parties' NDC targets toward 2030. This could in turn make NDC targets for the next trading period less ambitious than otherwise. Parties are expected to fulfill their self-committed 10-year targets, and aim much less at the longer-term and more difficult goal of net-zero.

A second problem arises when the ITMO price is positive but low, and there is weak support from climate finance. Carbon emissions can then be reduced but not in a "transformative" way, as fossil-fuel consumption still remains important in the parties' energy portfolios. Once emission-reducing but non-transformative investment costs have been sunk, the host can remain for long in a non-transformative equilibrium which prevents reaching the net-zero. The implication is, paradoxically, that an "intermediate" solution (where a low-carbon technology is implemented, using a positive but moderate carbon price) could be worse for our ability to stay on a transformative path, than doing nothing today to reduce carbon emissions. In principle this problem can be avoided by implementing complementary policies such as regulatory policies simply phasing out certain technologies that would be viable under low carbon prices. In practice agreeing and implementing the right package of complementary policies to "heal" a too low carbon price is highly complicated.

A third problem stems from capital market imperfections. Most renewable energy investments imply high up-front capital costs with very long payoff periods. These factors can limit the ability to raise private investment funds in many EMDEs and from international creditors. Interest rates on such loans tend to be (much) higher than in high-income countries (HICs), in part due to higher perceived risks to investors, and less developed and thinner credit and capital markets. This can dramatically raise the bar in EMDEs, and even more in LICs, for renewable energy projects to be attractive to private investors. High support by concessional climate finance may be required to overcome these barriers. If the PA is not backed up by such donor finance, it may fail to provide a basis for attaining the NZE.

Long-run transformative policies supported by climate finance can lessen some of these problems. Non-transformative solutions can be given less support in credit and financial markets, and transformative solutions more support. Climate finance can be directed specifically toward support to transformative solutions.

There could be serious obstacles to reaching an NZE in time also when global mitigation in the current period turns out to be deficient, and the ITMO price is high as many parties seek to purchase ITMOs to cover their NDC deficits. Since the PA is non-binding (and not actively being enforced), this could lead parties to abandon the treaty, reducing its global relevance.

The latest UN report (UNFCCC 2022) indicates that, when summing up the NDC pledges as made by September 2022, global net GHG emissions by 2030 are predicted at 49-56 gigatons (GT) CO_2e; similar to global GHG emissions in 2019, 52 GT. This report predicts global GHG emissions to peak around 2025, but that emissions will be reduced little by 2030 absent a dramatic tightening of parties' NDC targets. The UNEP 2021 report, only slightly more uplifting, predicts that global GHG emissions will be reduced by 4.5 GT CO_2e from 2019 to 2030, and that we are now far away from the NZE trajectory. Similarly, the IPCC 2023 requires that global GHG emissions be reduced to 33 GT by 2030, and to 18 GT by 2040, for the world to be on a 1.5 degrees C path.

Focusing on carbon emissions, the most important climate gas, the International Energy Agency (IEA 2021) predicts that global carbon emissions need to be reduced by about 40%, from a peak of 36 GT in 2019 to 21 GT by 2030, to be on a realistic path to NZE by 2050. This is dramatically lower than what is implied by current NDC pledges, about 31 GT. Other papers, such as Bertram et al. 2020, stress that reducing global carbon emissions by about a third is required up to 2030 to stay on track to a 2050 NZE. We are currently not on track to such a reduction.

Three recent IMF reports (Black et al. 2021, 2022a, b) also confirm that the world is currently not on track to a 2050 NZE. Reductions in global CO_2 emissions by 25-50% by 2030 are required to stay on such a path. Current NDC pledges imply only a 14% reduction in global CO_2 emissions over this period. Current NDC pledges are thus not aligned with most countries' net-zero targets by 2050-2070. Black et al. 2022a argue that comprehensive carbon prices of \$75, \$50 and \$25 per ton CO_2 must be imposed already by 2025 in HICs, EMDEs and LICs, respectively, to realistically reach this goal. Carbon prices are in almost all EMDEs today below \$5 per ton CO_2e, and in LICs almost nonexistent. This overall view is confirmed by Rogelj et al. 2023, who claim that there has recently been a decisive shift in the international climate policy sphere, from relatively unambitious “policies” to much more ambitious “targets” that are not justified by the actually maintained policies.

Other recent reports have similar conclusions but are slightly more positive. Ives et al. 2021 argue that the cost trajectory for PV and wind power are more favorable than projected by the IEA and UNFCCC, making it possible to ensure an NZE by 2050 even with little reduction in other climate gases, and with hardly any use of CCUS.

Box 1: Assessment criteria for reaching PA targets, MDB-supported operations (MDBs 2021)

Specific Assessment Criteria 1-5 (SC1-SC5) for MDB-supported operations for reaching the PA targets. (Negative answer to the respective question implies compatibility with the criteria.)

SC1: Is the operation/economic activity inconsistent with the NDC of the country in which it takes place?

SC2: Is the operation/economic activity, over its lifetime, inconsistent with the country’s LTS or other similar long-term national economy-wide, sectoral, or regional low-GHG strategies compatible with the mitigation goals of the Paris Agreement?

SC3: Is the operation/economic activity inconsistent with global sector-specific decarbonization pathways in line with the Paris Agreement mitigation goals, considering countries’ common but differentiated responsibilities and respective capabilities?

SC4: Does the operation/economic activity prevent opportunities to transition to Paris-aligned activities, OR primarily support or directly depend on non-aligned activities in a specific country/sectoral context?

SC5: Is the operation/economic activity economically unviable, when taking into account the risks of stranded assets and transition risks in the national/sectoral context?

Source: Joint MDB Assessment Network 2021.

Box 1 presents a short-hand framework for evaluating whether a policy or operation is aligned with a long-term strategy (LTS) developed jointly by the multilateral development banks (MDBs), here identified with a net-zero solution (by 2050 or beyond), and at the same time aligned with reaching the PA targets, both the medium-run targets (reaching countries NDCs by 2030), and long-run targets (staying within the 2.0 or 1.5 degrees Celsius average global warming). This is key also here: Are the medium-run NDC targets compatible with long-run net-zero targets? Note that this methodology established by the MDBs is a “not-doing-harm” approach, not an intertemporal optimization procedure for reaching an NZE by 2050.

In section 4 we discuss the possibility that increased climate finance from donors can speed up the net-zero transition, focusing on 1) project finance provided up-front to help overcome finance scarcity and imperfect capital and credit markets; and 2) results-based climate finance (RBCF), provided to host governments to stimulate implementing mitigation-inducing climate policies, focusing on comprehensive carbon taxation. We model such support and show that RBCF, paid to host governments as rewards for carbon tax implementation, can substantially increase these countries’ GHG mitigation, and speed up the path to the NZE.

Section 5 considers the NZE issue more directly. We ask: can a solution with net-zero global GHG emissions, by around 2050, be reached? We first consider the need for, and availability of, negative emissions technologies (NETs). Since some GHG emissions can never be avoided, feasibility of a global NZE requires the use of NETs. “Net-zero” needs not (and should not) be applied to any particular country or region. If one region has positive net GHG emissions, the rest of the world needs to have negative emissions, for the world to be in NZE balance. It is then important whether some countries, or regions, are willing to take on the “burden” of negative net GHG emissions; and/or be willing to set net negative GHG emissions targets. We here also study a simple model to illustrate these options and possibilities.

2. Limitations of the carbon markets for achieving net-zero under the PA

We will in this section discuss some issues which can be useful for understanding whether the trading mechanisms under Article 6 of the PA can help to incentivize a 2050 NZE, or whether it can be a drawback for such incentivization. Appendix A contains a simple model which provides the analytical underpinnings of the conclusions drawn here.

Given two fossil fuels for producing energy, one “dirty” fuel (coal), and one “intermediate” fuel (natural gas) with a lower but positive carbon content, incentives should be created to phase out coal; this is not in question nor complex to model.[3] A less obvious issue is whether, and when, to start phasing out an intermediate fuel such as natural gas. Should natural gas serve as a “transition

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[3] For the fuller argument that coal needs to be phased out completely by around 2050-2070 starting now, including a plan to do so, see Adrian et al. 2022.

fuel" toward an NZE; or should the energy development imply "leap-frogging", by moving directly from coal to renewables? A possible advantage of a transition solution could be that not sufficient renewables-based power-generating capacity can be established in the short run, due to capacity constraints in the renewables sector and/or credit market constraints. On the other hand, one can get stuck in a transition solution, as it may make the further transition to the transformative (zero-carbon) solution more difficult.[4]

2.1 Capital costs required for fossil fuel expansion

The host country's energy market can here be characterized by three choice options: 1) The host keeps its energy use constant, or expands its use of "dirty" fuels (coal-fired power); 2) the host expands its production capacity for "intermediate" fossil fuels (gas-fired power); and 3) the host expands its production capacity and use of "transformative" energy (renewables).

The choice between 2) and 3) is particularly important. Expanding the energy production capacity may be less costly using intermediate solutions than using transformative (renewable energy) solutions, but will cost more in terms of variable fossil-fuel inputs, as variable costs of renewables are virtually zero. This is the case despite, as demonstrated by recent literature, levelized unit capital costs for many types of renewables by now have fallen to a level equal to or even below unit capital costs for fossil-fuel technologies; see e g. Lazard (2021), IRENA (2020), Timilsina (2021).[5] This could lead one to think that emphasizing the possibility that fossil fuels could be preferable to renewables, or even a viable energy alternative, is not useful, in particular as future developments seem to progress toward lower capital costs for renewables such as solar PV and wind. But this argument is erroneous, for reasons not considered in our model: capital and credit market imperfections; high effective interest rates in many EMDEs; and institutional failures and technical capacity problems related to renewable energy projects. Thus, in many EMDEs, fossil-fuel based energy projects are still highly competitive, relative to renewables projects.

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[4] These are serious problems despite the principle set up under both Article 6.2 and 6.4 of the PA, that: "Each participating Party shall ensure that its participation contributes to … the long-term goals of the Paris Agreement". The problem is that adhering to this goal is extremely difficult to enforce; and that incentives created under the PA are not sufficiently aligned with the goal.

[5] See also the levelized energy cost calculated developed by the IEA: https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-electricity-calculator

Carbon pricing affects this calculus. With no carbon pricing, an initial choice of dirty infrastructure may be kept. But this may change with a positive carbon price, through the ITMO market and/or via comprehensive domestic carbon pricing in the host country, which can easily make the dirty alternative more expensive relative to investing in the intermediate alternative. When the carbon price increases by more, investing in transformative energy (renewables) will be the preferred alternative for expansion of the power sector, as indicated in the cited literature.

Table 2.1 illustrates such choices for different levels of the carbon price facing the host, given that expansion of production capacity is required for increased production of both intermediate (natural gas) and transformative (renewables) power output. The parametric details and derivations are found in Appendix 1. In this (stylized, and hypothetical) example, building new gas-fired power plants is the preferred alternative given a carbon price below \$20/ton CO_2, while expanding power capacity based on renewables is chosen when the carbon price is higher. The condition under which renewables are preferred, derived in Appendix A, is

$$(2.1) \qquad q > r(c_R - c_F) - p ,$$

where q = the carbon price, p = unit cost of the natural gas input, r = market interest rate, and c_F and c_R = unit costs of gas-based and renewable investments.

Both the market interest rate and unit investment costs are likely to differ greatly across countries, with higher values in EMDEs than in HICs, and much higher in LICs. Renewable investment costs are likely to be particularly high, as such projects have all their costs tied up in investment with long lifetimes which will appear highly uncertain to investors. Having in mind vulnerable EMDEs and LICs, we focus on cases where actual investment costs per unit of invested energy capacity is (much) higher than the relevant variable costs, and where investment costs are (much) higher for renewables than for gas-fueled power generation. Consider then a representative example where rc_R = 100, and rc_F = 50, so that the renewable-energy infrastructure (including power plant construction, grid expansion, and power storage facilities), per unit of net power delivered, is twice as expensive as the cost of constructing gas-fired power plants; and p = 30. This means that levelized investment costs for gas-fired power exceed (market-based) variable costs; and that effective investment costs are twice as high for renewables as for gas plants.

The choice of technology for new power will determine the country's power output for a long future time, perhaps up to 50 years. This investment alternative is thus highly important for this country's ability to reach or approach, and contribute to, an NZE by "around" 2050. Natural gas-based power will greatly reduce emissions, given that this replaces coal for power generation. But it will not remove carbon emissions from the power sector.

For example, when the early ITMO market (starting around 2025) leads to an ITMO price of \$16/ton CO_2e forward to 2030, the building of new gas-based power plants will be incentivized, but not new renewable-based capacity.[6]

Table 2.1: Numerical example of technology choice for the power sector, for varying carbon prices, when investments are required for "intermediate" expansion

Technology choice for the power sector	Carbon price in stylized example, \$/ton CO_2
Retaining initial "dirty" technology (coal)	< 5
Expanding "intermediate" technology (natural gas)	5-20
Switching to "transformative" technology (renewable energy)	Greater than 20

Source: Numerical example presented in Appendix 1

We next ask what levels of carbon pricing are likely to prevail in the current PA implementation period (up to 2030), and beyond.[7] We argue that carbon prices in the ITMO market under the PA are likely to be moderate at least up to 2030. With our numerical example, if the carbon price (facing most MEDEs/LICs) is below \$20/ton CO_2e, natural gas-based power will, under our example, be enabled instead of renewables-based power up to 2030. The PA trading mechanisms will then contribute to cementing an electric power structure less carbon intensive than a coal-based structure, but still based on fossil fuels and not compatible with an NZE. It may also make it harder for host governments to take on the (drastically) more ambitious NDC targets necessary to reach an NZE by mid-century.

2.2 Capital costs for fossil-based power capacity expansion not required

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[6] Formally, this requires that all actors view the current carbon price as given and constant over time. This is assumed here as a practically realistic "shortcut"; more complex future carbon price expectation formation might modify this rule.

[7] Most countries have chosen the target year of 2030 for their first NDC. Although, the PA does not speak about implementation periods, we use this term for simplification referring to the most common NDC practice.

We now assume that further expansion of "intermediate" (natural gas-based) power capacity is not relevant, because there is vacant (unused) capacity in this sector, or because any capacity expansions will be covered by renewables. We consider a later stage of the PA implementation process, closer to the mid-century at which point further investments in fossil-fuel-based power capacity will be ruled out, and the key issue is how quickly to phase out such capacity. Our goal is to study the speed of such phase-out, and the role played by the PA. A key issue is the condition under which existing capacity for natural gas-based power generation will be replaced by renewables. This is similar to the issue addressed in subsection 2.1, except that investments in gas-fueled power are no longer needed.

Table 2.2: Numerical example of technology choice for the power sector, for varying carbon prices, given no new investment in "intermediate" energy

Alternative for the power sector	Carbon price in stylized example, \$/ton CO_2
Retaining initial "dirty" technology (coal)	< 5
Scaling up energy supply by investing in renewable energy	Greater than 20
Switching from natural gas to renewables	Greater than 70

Source: Numerical example presented in Appendix 1

A consequential issue is the impact of a host country's earlier decision to invest, or not invest, in natural gas technology (up to 2030), illustrated in Table 2.2. If no natural gas investments had been made early, the choice situation in Table 2.2 would have been the same as in Table 2.1: investments in renewables if and only if the carbon price exceeds \$20/ton CO_2. When instead the natural gas investments are made early, a later scale-up of renewables investments, together with a divestment in gas-fueled power, can only happen at a (much) higher carbon price level.

This condition on the carbon price in the host country, for a switch from existing gas-fueled power to renewable energy, is found in Appendix 1:

$$q > rc_R - p \, . \tag{2.2}$$

Switching from natural gas to renewables involves investments only in renewables. Using our previous numerical example ($rc_R = 100$, $p = 30$), this switch occurs when the carbon price is at least \$70/ton CO_2. For carbon prices between \$20 and \$70, a scaling-up of renewable energy investments can take place. But *replacing gas-fueled energy infrastructure with renewables* occurs only when the carbon price exceeds $70.

Consider ITMO prices facing EMDEs/LICs under the PA up to 2030, which are positive but moderate (say, between $10 and $20). New gas-fueled power infrastructure will then be incentivized in these economies, as illustrated in Table 2.1 above. Our conclusion from the current subsection is that such infrastructure will be hard to phase out later; in our numerical example only when the ITMO price reaches $70.

When renewables are the only energy supply for the power sector compatible with an NZE, this host economy could end up with a large amount of “stranded assets” in the form of fossil-based energy generation capacity which is no longer needed. This is not formally modeled in this paper, but could add to the perceived costs (or reduced benefits) of the energy transition from fossils to renewables. Some influential actors (including the fossil-fuel industry) are likely to view it as inefficient to scrap large capital stocks with no opportunity value. Policy makers may also refuse to admit their (faulty) capital investment decisions, which may have occurred recently.[8]

Had there instead been a carbon price equal to zero early, no gas-fueled energy investments would then have taken place, as the host would have remained for a longer time with its coal-fired power plants. With a later (up to 2050) ITMO price in the range $20 - $70, a scale-up of renewable energy investments would have replaced the initial coal-fired energy infrastructure. The host economy would then (by 2050) be purged of its fossil-fuel use for electricity generation.

When instead additional investments had been made early by the host, to replace its coal-fired power plants with gas-fueled plants, and the ITMO price increases to a level between $20 and $70 in following PA implementation period or periods, this host will remain “stuck” with gas-based power infrastructure. Only when the ITMO price hits $70 will the gas-fired plants will be replaced with new renewable energy capacity.

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[8] See examples discussed in Adrian et al. 2022, and Prasad et al. 2022, Box 4. They argue that, in by far most cases, replacing coal-fired power plants with renewable energy plants is beneficial over gas-fired plants, as a long-run strategy. But once the replacement with gas plants has been made, and the related capital costs sunk, gas-fired electricity can be cheaper to produce than building the necessary new renewables facilities. See also Kalkuhl et al. 2012, Acemoglu et al. 2019.

A lesson from this exercise is that an initial, positive but low early ITMO price can create barriers against phasing out electricity generation based on gas and adoption of renewable energy, when this low ITMO price has already incentivized the investments in gas-based power supply.

We have in this section so far focused our attention on the electric power sector. Choices between "dirty", "intermediate" and "transformative" energy alternatives are however relevant also for other energy choices. One important sector is road transport, where the "dirty" case can be associated with traditional internal combustion engine (ICE) vehicles, the "intermediate" case is hybrid vehicles, and the "transformative" case is plug-in electric vehicles (EVs). A large uptake of EVs requires heavy public investments in electric charging technology, as well as heavy international R&D effort to bring EV costs down and their driving range up to competitive levels. *Robust carbon pricing* will favor EV uptake by making fuels for ICE vehicles more expensive; and make ICE vehicles more expensive relative to hybrids. *Positive but low carbon prices* can lead to high hybrid vehicle uptake but low investments in charging technology, serving to cement the "intermediate" solution, and making the transformative (EV) solution more difficult to reach.

Developments until now can make us pessimistic about whether "transformative" developments will likely happen under early phases of the PA. Most countries' aggregate NDC targets, and the overall global target level, are today far from sufficiently constraining for the current GHG mitigation path to correspond to an NZE by 2050. The willingness of investors to take on sufficient costly energy investment projects to stay on a transformative course is also uncertain.

3. Impacts of "low" early ITMO prices in a two-period dynamic model

Banking of carbon assets (ITMOs), accumulated by 2030 for later PA implementation periods, is prohibited under current Article 6 rules (see discussions in Strand 2022 and Greiner 2023). The PA however allows for crediting of current projects also in following implementation periods, as long as the projects' emission reductions can be credited also in those future trading periods, as is typically the case for renewable energy projects such as wind and solar PV farms.

There is a worry that the banking ban can lead to low ITMO prices (under both Articles 6.2 and 6.4) in the period up to 2030, and possibly beyond that date.[9] This is in part due to uncertainty about whether several parties' NDC targets might be over-fulfilled when approaching 2030. Under

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[9] See Strand 2022 for the fuller argument.

normal circumstances, over-fulfillment should have a high probability to occur for a party that aims to fulfill its target for certain on its own. Such an outcome becomes more likely in states of the world where investment opportunities are more plentiful, renewables investment costs are lower, and domestic demand for fossil fuels is lower. Such outcomes or states tend to be positively correlated across countries as they are often driven by global developments, and could easily result in an over-supply of ITMOs in the period approaching 2030, with a collapse of the ITMO price when ITMO banking is not allowed. An anticipation of such a possible price collapse is likely to deter global mitigation up to 2030. Such an outcome is made more likely by current decisions by both the E.U. and U.S., large potential ITMO buyers, to not use the Article 6 mechanisms.

Strand 2022 also emphasizes that the prevailing ITMO market near 2030 could have a “knife’s edge” feature which leads this price to be highly uncertain. ITMO targets then cannot be over-fulfilled (as ITMOs are not bankable); but these targets can neither be under-fulfilled (as parties’ pledged NDCs need to be fulfilled by 2030). When off the knife’s edge, the ITMO price will in 2030 tend to be either very low, or very high. In expectation, much speaks for the ITMO price to be low, as parties in under-balance may instead choose to default on their set NDC targets if the ITMO price is high; this will place limits on potentially high ITMO prices.

Given a banking ban, we cannot expect the carbon price in the ITMO market to follow a smooth path toward an NZE by 2050 or beyond. More likely, the spot ITMO price will be low, albeit uncertain, up to 2030. Most ITMO transactions will likely be executed bilaterally (under Article 6.2), with ITMO prices individually bargained between the seller and buyer country. What happens later is unclear as we do not know whether the banking ban will be continued beyond 2030.

As a consequence, the banking ban can reduce mitigation up to 2030 due to its potentially depressing impact on the ITMO price. This may limit the amount of carbon credits that can be awarded to long-term renewable energy projects through (ITMO) offsets, for given ITMO prices. This weakens the ITMO market as a mechanism for incentivizing global GHG mitigation.

The ability of the PA mechanisms to stimulate global mitigation as required for reaching net-zero by around 2050, is however largely determined by (binding) NDC targets for PA parties. When the Article 6 mechanisms work well, and support a robust and smooth ITMO price path over a longer period, NDC targets could be greatly strengthened over time, paving the way for a global mitigation path more in line with the NZE target.

In Appendix B we present a model that is more elaborate than that in Appendix A, and can support some of these arguments. We specify two trading periods for ITMOs, up to 2030, and beyond that date. In each period, the cost of new, and efficient, renewable energy investments is assumed as a quadratic function of the amount of new renewable investments made, with falling marginal productivity in new investments. The quadratic term is justified by two factors: a) the "best" renewable projects being implemented first, and b) political and financing costs which may limit the amount of renewable investments that are practically implementable in a given period. We assume that no new investments are made for fossil fuels. The amount of fossil fuels used in the host economy is instead being *scaled down*, replaced by renewables, at alternative rates that are impacted by the carbon market price in the two periods.

Carbon crediting is allowed for future implementation periods, but ITMOs cannot be transferred between periods, following from the ban on ITMO banking. As argued above, the ITMO price is then likely to be low up to 2030, but could be higher later.[10] The first implementation period lasts for n years, while the second period is (schematically) assumed to last for the remainder of time.

Our focus in this chapter is on impacts of different values of q_1 and q_2, the ITMO prices in the two periods, on hosts' fossil-fuel use, and their phasing-in of renewable energy investments. The model provides closed-form solutions to the host's consumption of fossil fuels and investments in new renewable energy capacity in each of the two periods, as functions of q_1 and q_2.

A particular concern is whether a low q_1, likely to prevail in the ITMO market under the current PA implementation period, can lead to problems with reaching an NZE by (around) 2050. We find that q_1 and q_2 have two main direct effects: a higher q_i increases renewable energy investments in period i, while it reduces total energy consumption. As a consequence, fossil-fuel consumption is reduced by even more in each period. In our linear-quadratic model these impacts are proportional to the ITMO prices. This means that a low carbon price in period 1 slows down both the fossil-fuel phase-out, and the renewable energy investment build-up; both developments are reduced to levels not compatible with an NZE by 2050. Also, this early slowdown is very difficult to counteract later as it cannot easily be overcome by greater effort at a later stage, in period 2.

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[10] Parties have however tendencies to emphasize current policies, and the current implementation period, as stressed by Bertram et al.2022.

Another result from our model, which further slows down the net-zero transition, is the impact of a "high" expected future ITMO price, q_2, following a "low" q_1. A problem then arises when the period 1 carbon emission level is the baseline for period 2 carbon trading. A higher emission level in period 1 will then increase the host's potential ITMO sales in period 2. This gives the host incentives to maintain a high fossil fuel consumption in period 1, to take advantage of higher ITMO sales in period 2; this at the same time slows down the NZE transition.

An important related issue, not explicitly built into the current model, is that future renewable investment costs are likely to be reduced by a high early investment volume due to learning-by-doing and improved technological progress in the renewable energy sector. This makes it globally efficient to provide a large early volume of renewable investments in order to spur learning-by-doing and technological innovation. Such considerations make it efficient to further *increase* the early (period 1) carbon price, instead of having this price *reduced* as is very likely to occur under the PA.[11] This enhances the problem that the PA will incentivize too little renewable investments, and too little mitigation, in its first implementation period.

A banking ban can also contribute to weaker future NDC targets, and can delay global mitigation, unlikely to be fully caught up by higher mitigation in subsequent periods.

4. Impacts of climate finance for reaching an NZE

4.1 Principal roles of climate finance

So far we have not discussed roles for climate finance in reaching net-zero. For most EMDEs and LICs, however, access to climate finance, and the way in which it is provided, can be crucial for their fossil-fuel use to be deeply cut (or virtually eliminated) by mid-century. First, from the discussion above, the net-zero transition will require large energy-sector investments, which may need support by climate finance. But as importantly, climate finance, in the form of results-based climate finance, RBCF, in response to achieved mitigation goals by hosts, can help to incentivize and enable more ambitious climate policies in host countries over this crucial period.

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[11] For literature supporting the argument that a further increase in the global carbon price level is optimal for this reason, see among others Newell et al. 1999, Gillingham et al.2008, Greaker et al. 2018, Liu and Yamagami 2018, Calel 2020, Barrett 2021, Grubb et al. 2021, and Way et al. 2022.

By far most finance required for NZE implementation will need to come from the private sector, either local investors or international capital markets. This represents a huge challenge to the global community; see among others Cooney and Oppermann 2020; Bhattacharya et al. 2022; Sandler and Schrag 2022; Stretton 2022a; and Neunuebel et al. 2022 for further discussion and analysis. Prasad et al. 2022 identify alternative ways to mobilize private finance. While climate-labeled private finance has increased substantially over late years, it is worrying to recognize that it still makes up only less than 0.3% of total assets under management (AUM) in international capital markets, substantially less than primary financing of fossil fuel-sector investments.[12] The share is particularly small in EMDEs and LICs, held back by lack of carbon pricing and mature local and regional (credit, bond and equity) financial markets; and by high subjective investment risks facing investors in these countries. This subjective risk, combined with underdeveloped finance markets, may easily overwhelm the potentially positive impacts of low and falling unit investment costs for most renewables (documented in Timilsina 2021). In the model above such problems can be represented in different ways: by a high interest rate r for climate-related investments in EMDEs (and even more so in LICs); a higher unit cost of renewables investments, c_R; and a lower carbon price q; when compared with rates facing HICs.

Various policies are available to make these markets more liquid and effective. Arguably, robust carbon pricing represents the most important policy. But greater availability of green and sustainability-linked bonds represents a promising financing modality for both the private sector, public sectors in EMDEs, and even for IFIs (exemplified by IFC's recent green bond issues).[13]

Two key roles of climate finance are a) as up-front funding capital, collateral or first-line equity tranches for investors in renewable energy; and b) as results-based climate finance (RBCF) provided in response to delivery of climate-related policies or policy targets. Role a) mainly addresses the insufficient availability and high cost of finance for renewable investments, while role b) addresses a lack of incentives in host countries, for general mitigation, and to initiate and implement the types of energy projects required for the NZE transition.

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[12] See Prasad et al. 2022, page 8; see also https://ppawatch.org.

[13] See e. g. Stretton 2022b.

Both roles can be viewed in the context of support to both finance of projects implemented by the private sector, and as finance made available to the public sector in EMDEs.

Finance of type a) can both reduce the average current investment cost, c_{R1}, and reduce the interest rate, r; from equation (3.1) both impacts will be favorable to private investment financing in EMDEs. This impact can be made maximally strong when the shares of climate finance-supplied subsidies are offered as first-priority finance tranches (absorbing the first losses in cases of ex post financing deficits by the borrower).

RBCF can be even more critical for reaching the posted global NZE. This role has most to do with incentives to implement transformative mitigation policies and investment projects. RBCF can support governments' implementation of certain climate-related policies (carbon pricing; ambitious NDC targets; increased renewable energy capacity; reduced support to fossil fuels; various other energy-related institutional reforms such as for building codes and transportation systems). RBCF can be provided bilaterally by donors, or multilaterally by IFIs such as the World Bank or the GCF. Little RBCF has yet been provided. The World Bank is currently in charge of RBCF-based pilot funds such as the Transformative Carbon Asset Facility (TCAF), where a main objective is to test the effectiveness of the mechanism in practice. RBCF is viewed as an important part of the World Bank's agenda to contribute to and advise on how to achieve the net-zero transition; see World Bank 2023.

Roles a) and b) are not independent. When RBCF is used to (successfully) implement a higher rate of carbon taxation in the target country, this will also serve as a type a) role. The reason is that the willingness of private (domestic and international) investors to fund renewables investments will be far more certain the higher the expected return to such investments is, since a high domestic carbon tax makes renewables more competitive relative to fossil fuels. The returns to renewables investments are then tied to domestic carbon pricing in the target countries.

Climate finance can serve to overcome many of the problems raised by low carbon prices, and failure of the PA mechanisms to incentivize transformational energy developments required for the NZE transition. This applies both to up-front project financing, and to RBCF. Up-front financing serves to directly facilitate transformational energy investments which are not facilitated by the Article 6 markets. RBCF can on its side be provided only in response to transformational policies enacted in the respective host countries. This will be illustrated and exemplified better in the next subsection below.

Climate finance as up-front investment support

Finance support can be provided to reduce the capital cost c_R to investors in renewables projects in EMDEs/LICs; reduce their interest rate, r; or reduce project uncertainty. Up-front project finance support can be provided in (at least) three ways: as grants; as concessional equity finance (taking ownership shares in the respective projects); or as concessional debt finance (typically, with lower interest payments than the unaided market rate) on all or part of the required finance (Sandler and Scrag 2022). A fourth class of financial support can be provided as sovereign guarantees, to reduce project risk for the lender. Prasad et al. 2022 argue that when the public-sector supporter in the respective EMDE country takes on the first loss or equity tranche of the risk exposure profile, substantially reducing the risk exposure of additional private investors, it constitutes an effective form of concessional finance support. How much such first-loss exposure will be taken on by the public sector will depend on the economy's carbon pricing policy including possible energy subsidy exposure: a higher carbon price will typically allow for a higher private finance share of risky transformative investments.

We may here also separate between support to debt instruments which reduces the project cost, and support which reduces the interest rate on borrowed funds for project financing, or alternatively reduces uncertainty for private investors (with a lowering impact on the interest rate).

A further intervention by donors could be to make investments in "intermediate" fossil-fuel projects less attractive relative to renewables projects. This can stimulate upgrading from coal-fired power to renewables-based power, instead of to natural gas-fired power, and thus stimulate the long-term transition to net zero.

Results-based climate finance

Results-based climate finance (RBCF) can be provided by donors, IFIs or similar institutions as a response to particular climate-related targets or policies being reached or implemented by the host country receiving RBCF support. Such finance can be provided to influence hosts' incentives to pursue climate-related targets and policies (policy RBCF), or to improve the commercial viability of investment projects. We are here focusing on policy RBCF for its potentially large-scale transformative mitigation impact. Policies and targets of particular relevance are a) comprehensive carbon pricing or removal of energy subsidies; b) nationwide targets for elimination of fossil-fuel related investments; and c) policies favoring transformative energy-sector developments. See World Bank Group and Frankfurt School of Finance and Management 2017, and World Bank 2018 and 2023 for extensive discussions of how RBCF can be applied, and its limitations. See also Strand 2019, 2020, 2021 and 2022 for further discussion of modes of application of RBCF, with focus on LICs, and their relative efficiency.

RBCF can be provided with or without a corresponding adjustment requirement (CA). Most commonly, RBCF is provided without CA by allowing for ERs to be used for host country NDC compliance. RBCF comes with CA when a donor wants to contribute to net mitigation (the host country does the CA but not the buyer country). The buyer would simply cancel the purchased ITMOs, but could report the money spent to purchase the ITMOs as climate finance. It could not do so if the ITMOs were used for buyer country NDC compliance. Host countries could opt for selling these mitigation outcomes as ITMOs later. But since RBCF cannot be received for ITMOs that are later sold in the ITMO market, the receiver could undertake corresponding adjustments given that the donor is reimbursed for the received RBCF payments. Under such an approach RBCF could become a revolving carbon market catalyst. RBCF can however also be provided on condition that the receiving government's (unconditional) NDC target be tightened (made more ambitious) when GHG emissions are reduced due to the policy. In such cases no additional ITMOs can be sold in the carbon market by the host, and no corresponding adjustment is required.

A straightforward impact could occur when RBCF is provided to individual governments as an incentive scheme to implement carbon pricing (or carbon taxes).[14] This, and the cases mentioned, will be modeled and discussed below. Also, carbon taxation (or other forms of direct or implicit carbon pricing) can be imposed by individual PA parties on top of the market carbon price for ITMOs, for implementing the parties' unconditional NDC targets, together with tightening of these targets. RBCF can be paid to parties also in response to reaching more ambitious target levels for transformative renewables investments in period 1. While this may be difficult in some cases (as when the government and firms in a given country are severely credit constrained or face very high market interest rates), such financing may incentivize investments implemented by external

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[14] See Stretton 2022a.

private parties that will be less subject to credit market constraints, at least when provided the appropriate guarantees of future support conditional on successful project implementation.

We finally note that bond issuance, so far not discussed, can also be used to raise capital for GHG mitigation purposes, and function in ways similar to RBCF. An interesting example is Chile, which has recently issued the first sovereign sustainability-linked bond, whose characteristics differ depending on whether or not the issuer (the Chilean government) reaches particular, specified, climate policy targets. In this case, Chile cannot emit more than 95 million tons CO_2e annually by 2030, and must have at least 60% of its electricity production from renewable sources by 2032, to avoid a 25 basis points increase in the interest payout on the bond by 2034.[15] With such bond issuance, the issuing country imposes on itself certain climate policy targets that will later be costly to break. Such bonds are particularly attractive for climate-aligned funders willing to sacrifice (relatively small) net financial returns to assure that favorable climate action is being incentivized.[16] These types of bond issue also have the added benefit, relative to RBCF, that finance can be raised early.

4.2 Modelling RBCF to incentivize carbon taxation in host countries

We will now analyze a model to demonstrate the potential role of RBCF for increasing global GHG mitigation, thus helping to reach an NZE. We focus on RBCF to incentivize implementation of comprehensive and robust domestic carbon taxes in host countries.[17] This model, similar to that in section 2, is more elaborate as renewables investments by the host is modeled more realistically, as a continuous function of the ITMO price q, as we assume that different renewables projects in the host economy have different investment costs. The host country then faces an increasing supply function for renewables. A higher domestic carbon tax in the host country has two favorable effects for the donor: it reduces fossil fuel consumption and carbon emissions; and it increases the investment in renewable capital.

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[15] See Caldwell et al. 2023, page 38; Rojas 2022.

[16] More standard green bonds, issued for climate mitigation purposes, also typically have lower yields than other standard bonds, but most are not issued with similar policy contingencies.

[17] See Timilsina 2022 for wider arguments in favor of carbon taxation as the preferred way to incentivize increased GHG mitigation, and thus stimulate the net-zero transition.

When a host implements a comprehensive carbon tax *t*, to complement the ITMO market with carbon crediting price *q*, the total carbon price in the host economy is $q+t$.[18] This total carbon price will likely not be excessive, as both components *q* and *t* are likely to be low relative to a carbon price required for a clear path to NZE by 2050, at least up to 2030.

In this model, RBCF can be disbursed to the host in two different ways. One implies that the RBCF contribution is provided only if the domestic carbon tax in the receiver country is set at or above a minimum level defined by the donor. This is the most efficient mechanism to be used by the donor. The alternative is as a simple support to the host's implementation of a domestic carbon tax, such that the amount of support is an increasing function of the implemented carbon tax. We will in the following in this section focus on the first of these alternatives, and study two alternatives for such a policy. Appendix C addresses a wider range of cases, also using the alternative (and less efficient) disbursement method just mentioned.

Basic model

Consider the following (periodic) welfare function of the host government in this case:

$$(4.1) \qquad V_G = E - \frac{1}{2}\gamma E^2 - pE_F + q(H^* - E_F) - rc_0(E_R - E_{R0}) - \frac{1}{2}r(c_M - c_0)\frac{(E_R - E_{R0})^2}{E_M - E_{R0}} + F \ .$$

We are here back to a single-period model set-up where intertemporal aspects are ignored, and the focus is on donors' ability and incentive to support carbon tax implementation in relevant host countries. The model is essentially identical to the model structure used in sections 2 and 3 (and thus Appendices A and B), with a quadratic cost function for renewable energy investments. The unit (marginal) cost of investing in renewables increases (linearly) over a relevant domain for renewable capital from E_{R0} (the initial level of renewable energy capital) to an upper bound of E_M, with marginal investment cost increasing from a lower bound of c_0 to a higher cost bound of c_M.[19] Note that we are now back to a single-period formulation, similar to that applied in section 2.

The term containing *q* in equation (4.1) represents the host's net income from selling ITMOs in the Article 6 ITMO market, which depends on whether and to what degree the host's NDC

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[18] Timilsina 2009 has provided another proposal of a carbon tax, for implementation jointly with a carbon trading mechanism, as part of the CDM.

[19] This differs from the specification in sections 2-3, where the marginal investment cost for renewables was assumed constant and independent of investment volume.

constraint is over-fulfilled ($H^* > E_F$; the host is a net supplier of ITMOs), or under-fulfilled ($H^* < E_F$; the host needs to purchase ITMOs in the Article 6 market). In the following we only consider hosts that have positive ITMO sales.

When the host country implements a positive domestic carbon tax t, the domestic sector in the host country will be subject to two compounding carbon prices, q and t, making the effective carbon price in this economy $q + t$.[20]

The last term in (4.1) represents the RBCF transfer, F, from donors to the host country, in response to a desired change in the domestic carbon tax set by the host.

Several alternatives exist for specifying the relation between the incentivized domestic carbon tax, and F. One alternative is that F is a fixed amount, paid out only given that (at least) a specific, domestic, carbon tax, t, is implemented by the host. Such a reward scheme can provide an efficient mechanism for the donor, by compensating the host only for its deadweight loss (DWL) related to implementing the carbon tax, and is focused on in this presentation. [21]

An alternative scheme is where the donor support is proportional to the domestic carbon tax implemented by the host, and the ER induced by this tax. This support could take the form of simply the product of the tax and the induced ER:

$$F = t(E_{F0} - E_F)\,, \tag{4.2}$$

(4.2) represents an over-compensation: it is (in the linear mitigation case) exactly twice the level of the DWL to the host from implementing the required carbon tax.[22]

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[20] This is perhaps unfamiliar to many, but logical. Consider an economic unit in the host economy that mitigates carbon emissions below an initial (BAU) level. With this mitigation, the domestic unit carbon tax of t is avoided; and the mitigated carbon emissions unit can at the same time be sold in the ITMO market at a price of q. This yields an effective unit carbon price, for the private sector in the host country, equal to $q + t$.

[21] The DWL equals the so-called Harberger triangle, which here equals half of F in (4.2) below. See Hines 1999; see also Strand 2020 for another similar application.

[22] It is however shown, in Strand 2023, that when hosts have additional (political, technical, etc.) costs related to implementing the proposed carbon tax, the optimal compensation by the donor in certain cases takes the particular form (4.2), or something close to this form. This issue of whether (4.2) is optimal or not will however not be further pursued in this presentation.

The donor support could also be provided on condition that the host increases its NDC target on par with the reduction in carbon emissions which follows from the carbon tax, so that no additional net revenue accrues to the host from selling ITMOs.

F may alternatively also be provided in response to an increase in renewables investments instead of to reduction in carbon emissions.

The private-sector objective function for the host country is:

$$V_P = E - \frac{1}{2}\gamma E^2 - pE_F + q(H^* - E_F) - rc_0(E_R - E_{R0}) - \frac{1}{2}r(c_M - c_0)\frac{(E_R - E_{R0})^2}{E_M - E_{R0}} - tE_F\ . \tag{4.3}$$

The only difference between (4.1) and (4.3) is that in the former, the RBCF transfer from the donor, *F*, is added; while in the latter, the carbon tax cost, paid by the private sector to the government, tE_F, is subtracted.[23] Note that the term including q in (4.3), representing net private-sector revenues from net sales of ITMOs in the Article 6 market, is not eliminated even in cases where it is eliminated in (4.1).[24]

The first-order conditions for optimal choices of E_F and E_R by the private sector of the host economy are (where we now can assume equality in both relations):

$$\frac{\partial V_P}{\partial E_F} = 1 - \gamma E - p - q - t = 0 \tag{4.4}$$

$$\frac{\partial V_P}{\partial E_R} = 1 - \gamma E - r[c_0 + c(E_R - E_{R0})] = 0\ . \tag{4.5}$$

$c = (c_M - c_0)/(E_M - E_{R0})$ gives the slope of the relationship between the marginal unit capital cost and investment volume for renewable energy investments. From (4.4) - (4.5),

$$p + q + t = r[c_0 + c(E_R - E_{R0})]\ , \tag{4.6}$$

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[23] tE_F is not added to the government's objective function as the government fully internalizes this private-sector outlay. This item, and perhaps also all or part of the finance transfer *F* from donors to the government, can here in principle be transferred back to the private sector in lump-sum fashion, without this altering the analysis in the following.

[24] It is the responsibility of the host government, not of the private sector, to ensure that the private sector can trade in the ITMO market at price *q*, even when the host government needs to purchase NDCs back to ensure that either its NDC target will be fulfilled, or potentially upscaled. See the analysis in the following sub-sections.

so that

$$\frac{dE_R}{dt} = \frac{1}{rc}. \tag{4.7}$$

Thus, a higher carbon tax increases renewables investments. From (4.4),

$$\frac{dE}{dt} = -\frac{1}{\gamma}. \tag{4.8}$$

This yields the following relationship between E_F and t:

$$\frac{dE_F}{dt} = \frac{d(E - E_R)}{dt} = -\frac{1}{\gamma} - \frac{1}{rc} < 0. \tag{4.9}$$

The carbon tax t in the host economy reduces fossil fuel consumption (and carbon emissions) in two separate ways: 1) by substitution of renewables for fossil fuels (via (4.7)); and by reducing the overall energy consumption (with all reduction falling on fossil fuels).

In this simple model, the impact on E_F of an increase in t is constant (for valid values of t).[25] A unit (discrete) increase in the carbon tax then gives unit changes in E_R and E_F from (4.7) and (4.9).

An increased carbon tax reduces total energy consumption, and increases renewable energy use; both effects reduce fossil energy consumption and thus carbon emissions in the host economy.

4.3 Incentivizing domestic carbon taxation and increased NDC ambition in host countries with RBCF climate finance support

Case 1: Support to carbon taxation with upscaling of NDC target

We now study the impact of donor RBCF support. We focus first on a case where the ITMO market does not yet exist (which is the current situation). We also assume that, as a condition for receiving RBCF, the host's NDC mitigation target is required to be upscaled at the same rate as the ER induced by the RBCF support. This ensures that global mitigation increases by the same amount. When there is no ITMO market, there are no trading options for the host related to increased ER.

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[25] Note that for these conditions to hold, t cannot be "too large", as our solution needs to yield both $E_R \leq E_M$, and $E_F \geq 0$. We however generally assume that any realistic solution adheres to these two conditions.

The element $q(H^* - E_F)$ drops out of both equations (4.1) and (4.3). The analysis in subsection 4.2 is the same as before, except that we there set $q = 0$.

We assume that donor support is provided lump-sum, to exactly compensate the host government for the deadweight loss of imposing the carbon tax t. In the absence of support, we assume that the host government has no incentive to impose any carbon tax.

The total required compensation to the host is the DWL related to implementing the carbon tax. The donor's own gross gain is $v(E_0 - E_F)$ (the value to the donor, of the ER implemented on the basis of the imposed tax t), minus the minimum compensation the host needs to implement this mitigation. This difference equals:

$$(4.10) \qquad V_D = v(E_0 - E_F) - \frac{1}{2}t(E_0 - E_F) = \left(v - \frac{1}{2}t \right) At = vAt - \frac{At^2}{2} ,$$

with A given by

$$(4.11) \qquad A = -\frac{dE_F}{dt} = \frac{1}{\gamma} + \frac{1}{rc} .$$

Here v is the donor's "social cost of carbon", and E_{F0} is the host's carbon emissions before t is imposed. Maximizing (4.10) with respect to t, we find

$$(4.12) \qquad \frac{dV_D}{dt} = (v - t)A = 0 \Leftrightarrow t_1 = v .$$

t_1 is the optimal t from the point of view of the donor, implemented in the host economy. This tax simply equals the donor's social cost of carbon, v. This is however idealized as we consider no technical, administrative nor political problems with implementing this carbon tax in the host economy, which could be severe.

To repeat, the donor only needs to compensate the host for its DWL due to implementing the carbon taxation imposed by the donor. The donor does not need to compensate the host for missing ITMO revenues, as no such revenues are available when the ITMO market is not operative.

One can here think of the donor as incentivizing the host to strengthen, and make more ambitious, its NDC emissions target under the PA. On this basis, the host will later be allowed to freely sell ITMOs in the market, given further ER beyond the new target.

This scenario is of interest as means to overcome one key barrier to ITMO markets and to enable donor countries to follow a least-cost global mitigation strategy. The barrier consists in concerns to use ITMOs for compliance purposes if originating from countries with low ambition to avoid carbon prices in donor countries to drop below the critical level to achieve the needed transformational change. This issue is similar to that of linking ETSs where large differences in cap tightness can become a barrier. Enabling a least-cost strategy relates to opening ITMO markets once host countries have achieved a sufficiently high ambition level with the support of RBCF. This will generate cost savings for donor countries as compared to achieving their own targets with purely domestic measures. Such cost savings can compensate or even overcompensate initial costs of providing RBCF.

Case 2: Donor assistance to the host in reaching its NDC target

In the second case considered, the host country has not yet reached its (unconditional) NDC target and needs to reduce its GHG emissions to reach that target. The host can, in principle, reach this target by itself imposing a comprehensive domestic carbon tax, call it t^*. Assume that the host government's acceptance to impose its own domestic carbon tax (or other similar mitigation policy) is limited to a lower tax level, $t_G < t^*$. The donor recognizes that, out of a carbon tax t to be imposed in the host country, the host itself is willing to cover a share t_G, while the donor covers the rest, $t - t_G$.

The host is still not allowed to sell ITMOs in the carbon market; this holds for units mitigated up to its (unconditional) NDC target level, which is the case we consider.

Consider possible donor support to a comprehensive carbon tax up to the level t^*, required for the host to implement its unconditional NDC target.

We also now consider the case where only the host's DWL needs to be (precisely) replaced.[26] We focus then on cases where the total carbon tax, t, is no greater than t^*. With an optimal donor policy

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[26] Appendix C also discusses other cases, hereunder the case where the RBCF takes the form (4.2).

(where the host can be held to its reservation utility, the objective function of the donor takes the form:

$$(4.13) \qquad V_D = \left(v - \frac{t - t_G}{2} \right) tA.$$

(The DWL of the host here equals $t^2A/2$; and the donor needs to replace a fraction $(t - t_G)/t$ of this loss for t to be implemented by the host.)

Maximizing (4.13) with respect to t yields

$$(4.14) \qquad \frac{dV_D}{dt} = vA - tA + \frac{t_G}{2} A = 0 \Leftrightarrow t_2 = v + \frac{t_G}{2}.$$

t_2 is the total carbon tax implemented in the host economy, while $t_2 - t_G$ is the carbon tax support provided by the donor, which equals

$$(4.15) \qquad t_2 - t_G = v - \frac{t_G}{2}.$$

In this case the carbon tax considered optimal from the point of view of the donor, in (4.14), and here implemented with donor support in the host economy, is greater than the donor's value of carbon. The donor support, (4.15), is less than its value of carbon, smaller than in case 1.

The total carbon tax imposed in the host economy (up to t^*) is here t_2, while the support paid by the donor to the host per unit of mitigation is $t_2 - t_G$.

Consider the following cases:

If $t_2 < t^*$, this donor support is not sufficient for the host to reach its NDC target. Additional policies are needed for the host to reach this target.

If $t_2 = t^*$, the donor's optimal support is exactly sufficient for the host to reach its NDC target.

If $t_2 > t^*$, the NDC target will be over-reached. The host can then sell ITMOs in the market, today or when this market opens. The exact solution for the carbon tax is then not given by (4.15) but can be higher or lower than this level.

Further discussion of cases 1 and 2, and the possibility of inefficient solutions

Case 1 implies supporting the host to "overachieve" its NDC target, requiring ERs to remain in the host country as the host's NDC target is tightened as its emissions are reduced.

Case 2 instead implies supporting the host to achieve its NDC target.

A difference between the two is that case 2 implies support to reaching a target that the host has set itself. Case 1 is support to reach a target that is imposed on the host by the donor. These two cases are, as presented here, essentially equivalent as we assume that ITMO trading is not available in case 1, and not relevant in case 2. When there is an option to sell ITMOs in case 1, it may be argued that case 1 is more constraining (and "burdensome") on the host, as the target updating constrains the host from selling ITMOs. In case 2 such a constraint is imposed by the host itself. These issues are further discussed in Appendix C, where we also consider additional, including less efficient, solutions for donor support to hosts for implementing carbon taxation, and reasons why such solutions may be relevant.

Numerical example of RBCF transfers to hosts

How large are the required RBCF transfers from the donor to the host in these cases? Consider first case 1, setting v = \$50/ton CO_2, the carbon tax then supported. Assume that the ER induced in the host economy by this tax is 10 million tons of CO_2e. The transfer to the host would be one-half of \$50 times 10 million, equaling \$250 million. This is the transfer required to compensate the host for its deadweight loss. Under this scheme, the host enjoys no net gain from this transfer, nor any loss.

Consider next case 2, with t_G = \$20, and a total carbon price of t_2 = \$60/ton CO_2. The transfer to the host is \$240 million per year (given an ER of 12 million tons of CO_2 at the support rate of \$40/ton CO_2; ER is in our model proportional to the implemented carbon tax).

To say more about the impacts on the total carbon price in the host economy, we revert to the numerical example in subsection 2.2 above. Renewable energy investments would there be selected over natural gas-based investments whenever the ITMO price was at least \$20/t CO_2; and renewable energy investments would be chosen to replace (or "strand") gas-based energy capital. When the host implements a (comprehensive, domestic) carbon tax of \$20, the first hurdle is already exceeded (even with only a marginal ITMO price). The ITMO price however needs to exceed $50 to pass the second hurdle. In both cases, the domestic carbon tax can have a transformational impact when it exceeds a certain minimum level.

In our numerical examples above, the donor-supported carbon tax was $50 in case 1, and $60 in case 2. In both cases, this is at least as high as the "second hurdle" just considered. It may still be difficult to think of such carbon tax levels implemented in LICs, or even EMDEs, in the near future. Few HICs have such comprehensive carbon tax levels today.

An even more serious issue is that only very limited climate finance on a donor basis is available today, of any type. The current RBCF level (in total, from public and private sources) needs to be scaled up, dramatically and quickly, to contribute substantially to reaching an NZE by around 2050. According to CPI 2021,[27] aggregate global climate finance reached $650 billion in 2020, of which more than half went to EMDEs. Close to half of this was public funding; $400 billion took the form of debt, $210 billion equity, and only $38 billion was grants. CPI estimates that reaching net-zero requires a dramatic scaling-up of total annual climate finance, to around $3.5 trillion by 2025, $4 trillion by 2030, and $6 trillion by 2050.[28] A non-negligible part of this funding should be provided in terms of RBCF, with the primary objective to incentivize carbon pricing and domestic transformative project financing. We are today far away from such a path.

5. Solutions by 2050: Global net-zero[29]

We will now look toward 2050 and ask whether a net-zero solution can be realistic by that time frame and in case what properties an NZE is likely to have. Importantly, an NZE requires that negative emissions technologies (NETs) can realistically be applied by some countries, to counter other positive net GHG emissions. Some countries must also be required to implement net-negative emissions, and have incentives for such implementation. While this is not obvious, it will here simply be taken as given.

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[27] See also Prasad et al. 2022.

[28] Some of this funding is for adaptation; and close to $1 trillion per year represents funds diverted from fossil fuels to renewables and other new energy technologies.

[29] For clarifications and definitions of the concepts "net-zero", and "net zero solutions", see among others Allen et al. 2022, van Soest et al. 2021, Hale et al. 2022, Fankhauser et al. 2022, and Black et al. 2022a.

5.1 Global carbon capture, utilization and storage (CCUS) from energy sources and air capture

A net-zero solution for global GHG emissions by 2050 or somewhat later does not mean that all countries' emissions need to be zero, nor that fossil fuels and other GHGs than CO_2 (such as methane and N_2O) need to be eliminated. Negative emissions can be achieved in several ways, and for individual countries. Two main negative emissions technology (NET) alternatives are, first, carbon capture, utilization and storage (CCUS) from energy sources or directly from the air (direct air capture or DAC), limited by cost and the availability and convenience of storage capacity for the sequestered carbon. The second is various "nature-based solutions" (NBS) where carbon is captured and retained in three natural elements: vegetation, soil, and water. The most important of these, relevant for LICs, is the expansion of forest areas via reforestation and afforestation, limited by availability of area for forest expansion.

The International Energy Agency (IEA 2021) identifies 6 main NETs: a) fossil-fuel based power facilities; b) industrial processes (see Farrell 2018); c) hydrogen; d) other fuel production; e) bioenergy combined with CCUS (BECCS); and f) direct air capture (DAC). The IEA predicts that a global net-zero outcome could involve around 7.6 GT of CO_2 capture annually by 2050; see Table 5.1. This will imply a dramatic, 40-fold, scale-up of CCUS from now to 2050. The four first alternatives (a-d) reduce carbon emissions but do not lead to negative emissions; while the two last (e-f) are genuine NETs. The first four alternatives drastically reduce emissions in application areas where emissions otherwise are hard to eliminate or reduce. All these energy-intensive activities would otherwise have been virtually out of the question in the context of an NZE by 2050, since they can over this time span be expected to rely on fossil fuels to at least some degree.

The two last alternatives on the IEA's list, bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC), are however genuine NETs.[30]

To understand how BECCS can yield negative carbon emissions, recognize first that using biological material for fuel, electricity or heat production *without* CCUS is essentially a zero-carbon activity (ignoring fossil-fuel inputs applied for growing, harvesting and transporting the materials and outputs). Removing carbon from the combustion process using CCUS then leads to

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[30] Note that the IEA 2021 analysis does not include any nature-based NET options.

a negative carbon balance since the biological material, subsequently combusted, already has captured its carbon content based on photosynthesis. An extensive use of these two solutions by a given country can then lead to net negative GHG emissions from that country. In addition, NBS alternatives can also as noted contribute to net negative carbon emissions.

Table 5.1: Expected global volume of net carbon capture, utilization and storage from energy sources and air capture (CCUS) under NZE plan (IEA 2021).[31] Million tons of CO_2 per year by 2050.

Sector	2020	2030	2050
Fossil-fuel based power	3	340	860
Industrial processes	3	360	2620
Hydrogen production	3	455	1355
Other fuel production	30	170	410
Carbon capture from bioenergy	1	255	1380
Direct air capture	0	90	985
Total	40	1070	7600

Source: IEA 2021

Table 5.2 provides rough future cost estimates for CCUS alternatives, not including transport and storage costs of captured carbon. They comprise the IEA alternatives in Table 5.1, and in addition several NBS alternatives not included in the IEA assessment in Table 5.1. For some of these, costs appear manageable. The carbon capture costs are already moderate for coal and natural gas processing to chemicals (\$15-\$25), also for ethanol and ammonia production from bioenergy (\$25-\$40). Costs are currently higher for other applications, but manageable given carbon prices in the range recommended by Stiglitz and Stern 2017 (\$50-\$100 by 2030). Hopefully, costs can push toward the lower bounds, which appears likely as the sector is still nascent and can benefit highly from increased R&D and learning.

Importantly, two key NET solutions, BECCS and afforestation, can lead to large additional demands for land and thus be problematic in other respects (for example, by reducing global agricultural capacity and threatening biodiversity).

The potential for BECCS to yield large negative emissions by 2050 is also uncertain. Fuss et al. 2018 estimate that available bioenergy by 2050 has a wide (theoretical) range, 60-1500 EJ.[32] The land constraint is particularly uncertain, and depends in part of how much high-productive land

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[31] NZE = Net Zero Emissions by 2050 Scenario (IEA 2021)

[32] 1 EJ = 1 Exajoule = 10^{18} joules ≈ 278 TWh

(also suitable for agriculture) will be set aside for bioenergy production. Cornelissen et al. 2012 have argued that a "realistic" land constraint for bioenergy implies available bioenergy of about 340 EJ/year by 2050; this includes algae as feedstock in the amount of 90 EJ/year.

Table 5.2: Estimated net marginal costs of carbon capture, including sequestration costs, for alternative technologies, and theoretical sequestration potential for net-negative technologies, by around 2050. US$/ton CO_2, 2015 prices[33]

Technology alternative	Lower cost range	Upper cost range	Sequestration potential, Gt CO_2/year
Coal to chemicals	15	25	
Natural gas processing	15	25	
Bioethanol	25	40	
Ammonia	25	40	
Hydrogen	50	80	
Iron and steel processing	40	100	
Cement processing	60	120	
Power generation	50	100	
Bioenergy with CCS	60	200	0.5-10
Direct air capture	40	300	0.5-10
Afforestation and reforestation	5	50	0.5-3.6
Enhanced weathering	50	200	2-4
Ocean fertilization	55	300	0.2-5
Biochar	30	120	0.5-4
Soil carbon sequestration	0	0-100	2-5

Sources: Baylin-Stern and Berghout 2021, Fuss et al. 2018, Minx et al. 2018, Harrison 2017, Qiu et al. 2022.

A crucial factor regarding whether or not to apply CCUS alternatives is cost; another is safety and security of carbon transport and storage. CCUS (apart from NBS) consumes large amounts of energy. To consider whether there are private incentives to implement CCUS, a useful benchmark is the cost or removing one net ton of CO_2, relative to the carbon cost or price facing agents. For a government, the benchmark will be this government's evaluation of the damage caused by releasing one ton of CO_2.

The future viability of DAC

DAC is currently more expensive than most of the energy-based CCUS alternatives, and still not competitive when compared to other relevant CCUS solutions at current carbon prices. But DAC

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[33] Note that not all these alternatives are directly comparable as, in particular, storage using several of the NBS alternatives are not permanent. Considering the cost alternative for permanent storage, most of the NBS figures then need to be scaled up, but scaling factors are here not fully clear.

costs are likely to come down over time with more research and DAC activity at scale, and carbon prices are likely to increase. See Nemet et al. 2018 for discussion.

There are two relevant technical DAC solutions: high-temperature aqueous solutions (HT DAC); and low-temperature solid-sorbent solutions (LT DAC). Fasihi et al. 2019 argue that LT DAC solutions will over time tend to dominate cost-wise; and that the lower bound for DAC implementation costs will fall to around $50 per ton CO_2 by 2040, and potentially lower at later points of time, thus likely becoming competitive relative to other mitigation alternatives (including other CCUS alternatives) by that time. Similar results are found by Daniel et al. 2022, who stress two further factors: 1) the energy demand component of DAC is likely to become less expensive over time as cheaper renewable power generation solutions arise; and 2) captured carbon will in many cases have industrial uses that reduce overall net costs.

Since the atmosphere's CO_2 concentration is highly homogeneous, an advantage of DAC is that it can be applied anywhere and thus at the locations with least expensive access to non-carbon energy sources and underground storage facilities. Another advantage is the essentially unlimited scale of this technology. As a result, the unit cost of DAC can in practice serve as a cap on NET deployment cost: other technologies ought to be used only when it is cheaper than DAC.

DAC however also has limitations. A main limitation is that the DAC process itself is energy intensive. To indicate its energy requirements, if the process were executed with natural gas as the energy source (without carbon capture), the carbon release from the capturing process would at its current technological stage be 44-50% of the air-captured CO_2. Thus, even when the required energy for DAC is provided through renewable power or air-captured bioenergy, DAC activity at scale, required to secure a net-zero outcome, would require a non-negligible fraction of global energy supply. With respect to viability of different main DAC technologies (high-heat, solvent-based, and low-heat, sorbent-based) there currently seems to be some disagreement in the literature: while some studies (such as Madhu et al. 2021) favor low-heat technology, Qiu et al. 2022 points to lower overall environmental stress when applying the high-heat technology; although total costs are not fully accounted for in either of these studies. The estimated energy demand for the (high- and low-heat) DAC technologies also vary across studies, from about 200 kWh to more than 700 kWh per ton CO_2 sequestered. At the lowest energy cost in this range, using DAC to sequester 10 billion tons CO_2 annually requires 2000 TWh of electricity, or 7.2% of current global electricity supply (as of 2021); at a mid-range cost alternative (400 kWh/ton CO_2) this share is 14.4%.

The figures in Table 5.2 do not include transport and storage costs for captured CO_2 (a factor that increases the uncertainty related to overall costs and ranking of different NET alternatives), implying that total costs will be higher. Out of total captured carbon, more than 90% will be stored and the rest used, most for enhanced oil recovery (EOR) when pumped back to oil fields (which is also in the end stored), or for various other purposes including the chemical industry.

The economic costs of applying DAC at scale are still highly uncertain, as the technology is by now only tested at very limited scale and at the experimental level. Lackner and Azarabadi 2021 have developed an analytical “buy-down” model which indicates that the sequestration cost from applying the technology can be lowered to around \$100/ton CO_2 from applying a capital cost of \$500 million, on condition that the cost path is similar to those of other successful energy technologies (such as solar PV technologies). Athey et al. 2021 suggest a similar approach: That a party makes an Advance Market Commitment (AMC) (similar to those already made for certain global vaccines) to put up a funding of \$1 billion for development of DAC “at scale”, to get activity started for such developments. This will provide a strong signal to policy makers, scientists and investors that such funding is available. DAC can at the moment be viewed as a “last resort” when other options have been exhausted and more mitigation volume is necessary.

Nature-based NET solutions (NBS)

Smith et al. 2015, Griscom et al. 2017, Fuss et al. 2018, and Hepburn et al. 2019 discuss nature-based NET solutions (NBS) for net-negative emissions, not included in the IEA 2020 survey. The most accessible of these are forest carbon sequestration, afforestation and reforestation. A related alternative is to store wood products: Churkina et al. 2020 indicate a potential for carbon storage of wood used as construction material, of 20 GT over the next 30 years.[34] Other NBS involve carbon sequestration via plant life, water, and soil. The four most important currently appear to be

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[34] This alternative has the added benefit that wood, as construction material, to a large extent replaces steel and concrete that imply large emission burdens. Thus strong arguments exist for subsidizing such applications.

a) enhanced weathering (EW),[35] b) ocean fertilization,[36] c) biochar,[37] and d) soil carbon sequestration (SCS). These alternatives were, in the IEA 2021 report, considered as too little explored or policy-focused to be serious alternatives at scale by 2050; and may not be fully permanent (Edenhofer et al. 2023; Kalkuhl et al. 2022). But they are relevant, at moderate scales by 2050, and at greater scale later.

SCS appears particularly attractive by having few negative environmental impacts, and low (perhaps negative) net economic costs. Its relevant sequestration potential is 2-5 Gt CO_2/year by mid-century. Chambers et al. 2016 estimate that an increase in the carbon content of the top 20 cm for 70% of U.S. cropland by 0.4% annually (corresponding to the United Nations "4 per Thousand Initiative", from 2015) will sequester at least 0.3 Gt CO_2 annually in the U.S., and about 10 times more globally, with costs of \$4-\$12 per ton CO_2 sequestered. Chambers et al. 2016 also estimate that if the same relative improvement is achieved for the top 40 cm of soil in cropland, grassland and forests, the annual sequestration potential for SCS in the U.S. is about 0.8 Gt CO_2/year. This is attractive as it also serves to increase crop productivity (not considered in the cost alternatives), and can be implemented with simple tilling and cropping techniques. Its scope is however subject to saturation which will set on after a 20-year initial period. A similar situation occurs for ocean fertilization, where cost estimates are less precise (see Harrison 2017).

Cost and volume estimates for alternatives a-d are highly uncertain as they are based on modeling approaches and not on practical applications. Some alternatives will be limited due to competing land use; competitive land use issues are generally accounted for differently in alternative studies.

Soil carbon sequestration has a likely storage half-life of only decades; the same applies to biochar (Hepburn et al. 2019). Thus several NBS alternatives only postpone global carbon emission accumulation, and some only marginally. By contrast, DAC and BECCS alternatives can (with safe and stable storage sinks) safely store carbon for millennia.

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[35] Weathering is here defined as natural rock decomposition via chemical and physical processes. Enhanced weathering implies that rock is artificially decomposed and the residuals spread out across the area used for carbon absorption.

[36] The most relevant such alternatives are adding nitrogen, phosphorous, and iron to the ocean surface at relevant volume and cost levels, and in locations where it is most needed.

[37] Charcoal produced from plant matter and stored in the soil as a means of removing carbon dioxide from the atmosphere. See Woolf et al. 2021.

Overall considerations

Tables 5.1 and 5.2 seem to yield an optimistic potential for global carbon sequestration using CCUS by 2050. The IEA 2021 analysis as basis for Table A however only considers levels of CCUS that are part of a plan for net zero carbon emissions by 2050. Little is known about the realism of reaching that target, and implementing these CCUS levels, by mid-century. On the other hand, the IEA analysis ignores the NBS alternatives in Table 5.2, where the aggregate potential for carbon sequestration can be large. In terms of overall potential and costs, Griscom et al. 2017 estimate that NBS alternatives (apart from ocean fertilization) represent an annual sequestration potential of about 23 GT of CO_2, of which about 11 GT is economically interesting (with costs below \$100/ton CO_2), and 4 GT is cheap (with costs below \$10/ton CO_2). The forest-based alternatives and SCS appear particularly promising as costs are mostly lower than for carbon capture from energy in Table 5.1. But the NBS alternatives are subject to global constraints, mainly on land use. If they are applied aggressively early, their later applications will be constrained. Also, much or most of the NBS alternatives must be implemented in LICs where governance is generally poor and the ability to carry out the necessary action could be missing.

The costs and volumes for several NET alternatives are not independent. For example, greater afforestation/reforestation could reduce the amount of biomass available for bioenergy. There are also trade-offs between these alternatives and the global availability of agricultural land. The time profiles for some alternatives are also interdependent. If one alternative is used aggressively in an initial phase, that alternative may be costlier to use or be less available later. This can apply to all NBS alternatives, the 5 last alternatives in Table 5.2, and to BECCS. Storage alternatives and capacity will also at least in some cases be subject to saturation.

Some studies have attempted to calculate co-benefits, primarily to human health, from capturing carbon using different NETs. Cobo et al. 2022 focus on BECCS and DAC, and find that these provide human health benefits compared to a BAU alternative with no such activity.

There is however in the literature some skepticism toward the BECCS alternative as a long-term sequestration solution. Allen et al. 2022 argue that BECCS is more land intensive than most NBS options, and fails to yield multiple long-term benefits.

NET technologies can do two things: 1) buy time for bringing emissions down; and 2) allow for residual positive emissions in an NZE. BECCS and DAC can function indefinitely to compensate for residual GHG emissions (assuming unlimited storage space). The NBS alternatives generally cannot. For example, afforestation can only function up to growing forests to their maximal extension; which means that they at least can play the first role indicated.

Widespread use of carbon removal technologies leads to governance issues that need to be addressed and solved. One is how to embed carbon removal into trading schemes such as the EU-ETS which today does not allow for such technologies to be credited. One problem is related to non-permanent carbon removal, for example via NBS solutions where the degree of future carbon release to the atmosphere is positive but uncertain. This is an incipient area of analysis where results are today only tentative. Edenhofer et al. 2023 suggest principles for how to embed non-permanent storage into the EU-ETS. Kalkuhl et al. 2022 consider three alternative policy regimes for optimal carbon removal: downstream pricing, upstream pricing, and carbon storage pricing. While all these mechanisms can in principle implement an efficient solution, their informational requirements differ, and could be most favorable for upstream pricing. This is a field of active research which will be important for how to handle these governance issues, as they arise with more widespread application of NET solutions.

It is not a task for this paper to discuss whether any countries or regions, nor which countries, have better capacity to sequester carbon using NET technologies, and store carbon underground. This depends on regional features such as local geology and afforestation and bioenergy potentials. Tropical regions have higher bioenergy potential per land area, and more carbon is stored in tropical than other forests. LICs located in tropical areas therefore have the potential to earn large revenues from selling carbon assets including from NBS. HICs likely have a comparative advantage for implementing the more advanced and costly CCS technologies, in particular DAC.

5.2 Modeling GHG emission solutions by 2050 when NET alternatives are included

Appendix D presents a model similar to that in section 2, to illustrate the nature of an NZE solution by 2050 (or somewhat later), given that it is reached. We discuss key aspects of this solution: what drives it, how is overall GHG mitigation distributed between different world regions; and implications of an NZE for implementation costs and the distribution of costs and net revenues across countries. We explicitly model NETs, their costs, and roles.

This model provides a simplistic, and idealized, picture of an NZE in 2050, represented by a net-zero GHG emissions constraint (equation (D5)). The HIC region implements negative emissions activities, principally in terms of BECCS and DAC; while the residual region relies (mainly) on NBS NET alternatives. The model tells us a simple lesson: in an NZE, a positive net emission rate by one region must be countered by an equally large negative emission rate by the other region.

Which region will have positive and which will have negative net GHG emissions depends in part on the shapes of the regional fossil-fuel supply and NET functions. At the most basic level, when the first main term (carbon emissions from fossil-fuel consumption) dominates, net GHG emissions are positive; while when the second main term (carbon emissions reduction from CCS) dominates, net emissions are negative.

It may here be reasonable to assume that region 1 (HICs) will have net negative emissions, since CCS expenditures and activity are likely to be (far) greater in that region, and since region 1 is likely to have a (far) more ambitious GHG mitigation policy than region 2 (rest of the world), which will have net positive GHG emissions.[38] This can represent a high willingness to take on a large amount of relatively expensive CCS projects in region 1, with a correspondingly high implementation cost; while region 2 is much less willing to take on CCS projects.

Net carbon trading revenues for a given region will depend on the region's emission target relative to its emission rate. Thus, if region 1's GHG emission rate is negative, its target rate must be even more negative for region 1 to have negative, and region 2 positive, net carbon trading revenues.

This simple model describes an "idealized" ITMO market with centralized GHG emissions trading (see Edmonds et al. 2021), where all units are traded at a unified carbon price q^*, and all GHG emissions are optimal given the same carbon price. Optimal market efficiency is achieved only with a fully unified carbon market, with a common carbon price, which also will imply a subsidy for NET activities. The ITMO market functions equally well for negative as for positive GHG emissions levels of different individual actors and country parties. This is idealized but not realistic. More realistically, q will vary across countries and sectors in a given country, in particular since much of the ITMO trading may take place bilaterally (as will occur under Article 6.2 of the current PA), and typically at higher carbon prices for trading between higher-income regions. Also,

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[38] In the model of Appendix D, this can be the result when λ is "relatively small" and β "relatively large".

GHG emissions from different sectors in a given country or region are then likely to be priced differently.

Correspondingly, with a high average carbon price q_1 in region 1, and a lower carbon price q_2 in region 2, total GHG emissions in region 1 will be relatively lower, and in region 2 relatively higher. It is however difficult to say how this can affect the regions' net carbon trading surpluses, as the regional targets are endogenous in the long run, and may be strongly affected by emissions levels.

In this section we have not considered any specific role for climate finance. It is however clear that climate finance, and RBCF in particular, could play an even more important role than earlier, during the stages of closing up on the NZE, to make parties go the last step to reach it, maintain it, or go to net negative global GHG emissions. In particular, NET solutions which heavily involve the EMDE/LIC group may require substantial outside funding and technical assistance, for these countries to optimally use their NBS alternatives. RBCF schemes, for rewarding specific countries in this group for their willingness to use NETs at scale, may become necessary for enabling such developments, financially and in terms of the countries' incentives.

6. Conclusions

We have in this paper explored ways in which the future carbon market under Article 6 of the PA can reduce global mitigation costs dramatically, and positive emissions might need to be compensated by negative emissions, but where the current implementation environment (low ambitions and imperfect operating rules under Article 6, including a banking ban) risks to generate too low carbon prices, or might hold back the Article 6 carbon markets, making it impossible to reach NZE by close to targeted dates. Staying on a trajectory defined and guided by the PA depends first on target setting: are the parties' aggregate GHG emissions targets sufficiently restrictive to reach a global net-zero solution by 2050, 2060 or 2070? In practice the situation is more complicated since targets will be influenced by various features including incentive mechanisms and financial support; and the question remains whether targets will actually be achieved. The Article 6 mechanisms of the PA constitute an important part of the framework for potentially reaching an NZE. The paper has identified several ways in which the PA can influence the net-zero attainment. On the more positive side, we have discussed what can be done to improve the ability of the PA to serve such a positive role. This relates both to changes in the Article 6 rules, and to a potentially critical role for donor-provided results-based climate finance (RBCF), focusing on incentivizing carbon pricing in EMDEs/LICs.

An obstacle to reaching net-zero by these dates is that the carbon price in the ITMO markets could be low up to 2030, and perhaps beyond. As discussed in section 2, a positive but low carbon price up to 2030 could incentivize "intermediate" technology solutions and not more transformative solutions (gas-based instead of coal-based power generation; or low-emission ICE vehicles instead of EVs). This could hamper the achievement of transformative developments toward an NZE, which requires purging carbon emissions from virtually all economic activity. In our section 2 example, natural gas-fueled electric power capacity is expanded, instead of renewable capacity, when the ITMO price is \$10 - \$20/t CO_2. When this technology choice has been made, and its investment costs are sunk, the needed carbon price is much higher (in our example, to \$70) before additional renewable energy capacity is chosen to replace the gas-fueled capacity. If the investments in the gas technology had not been sunk early, this later carbon price would have been lower (in our example, \$20/t CO_2). A positive but low carbon price up to 2030 can then serve as a roadblock to an NZE development. It might even have been better with no early carbon pricing, as this would not have enabled the early switch from coal to gas.

A second important factor, stressed in section 3, is the current ban on banking of ITMOs across implementation periods, which is likely to depress the first-period ITMO price and mitigation up to 2030. A low carbon price reduces hoped-for mitigation during this period, and delays the NZE transition. If this banking ban is not reversed in future PA implementation periods, this problem may persist for a much longer time.

A third factor, also reducing the opportunity to reach an NZE by 2050, is the low renewable investment rate expected during the first PA implementation period. Investment in renewables should be stimulated early, as their larger early uptake reduces their future costs due to positive innovation and learning-by-doing impacts.

We also discuss how to rectify some of these deficiencies and the problems with reaching an NZE by 2050. One remedy is to drop the current banking ban and let ITMOs be traded across PA trading periods beyond 2030. Another is to dramatically scale up the supply of climate finance to EMDEs and LICs: up-front finance support to overcome credit and capital market imperfections that hold back renewable energy investments; and RBCF as "carrots" to governments to implement more forceful climate policies such as carbon taxation and renewable-sector support programs, and spur private investors to take on transformative renewable investment projects. Section 4 focuses on the role of RBCF for incentivizing carbon taxation in EMDE and LIC countries, to supplement the ITMO market with its own carbon price. We analyze a model where donors reward host governments for implementing comprehensive domestic carbon taxes. We derive optimal carbon taxes in host countries, from the point of view of donors which support such taxes. These taxes can be significant (in our constructed numerical examples \$50-\$60/t CO_2), and could be a game changer for EMDEs and LICs that today have no such taxes. They can induce substantial mitigation and renewable investments in the host countries, accelerating developments toward an NZE. Up-front subsidies to renewable investments can also help the NZE transition by overcoming financing barriers in imperfect credit markets, and promote further cost reductions for renewable technologies. It is difficult to foresee a net-zero transition for EMDEs and LICs by this time frame, without massive finance support to EMDE and LIC hosts.

Section 5 discusses likely future events and developments during the “end game” to an NZE. We first discuss alternative negative emissions technologies (NETs), with direct air capture (DAC), bioenergy with carbon capture and storage (BECCS), and several nature-based solutions (NBS) as the most significant. We consider a simple model of a future outcomes with low global GHG emissions, and NETs are applied to remove remaining gross GHG emissions, with two regions, HICs, and “the rest of the world”. The HIC region has a net-negative GHG target and emissions rate, while the residual region has positive target and emissions rates. Such a solution can be implemented technically, but may be politically problematic even for the HIC region, and perhaps difficult to accept if this region’s emission target is more negative than its emissions, required to provide net carbon trading revenues to the lower-income region. We have not discussed in detail political problems related to implementing such a solution, which might be serious.

This paper gives no answer to the question of whether a net-zero solution can or will be reached by 2050 or somewhat later. Reaching this target requires extraordinary efforts by all countries, and actors.

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Appendix A:

Capital costs required for fossil fuel expansion

Consider a simple model where capital expenditures may or may not be needed for capacity expansion of part of the fossil-fuel based energy use, while it is always needed for capacity expansion for renewables. We consider expanding "intermediate" fossil fuel consumption beyond its current use, which requires investments of c_F per unit of increased energy supply. We assume no delays for intermediate fossil-based investments (natural gas-based power plants; hybrid motor vehicles) as investors are more established and required investment volumes limited. We expect first-order conditions to hold with equality for fossil fuels. For renewables, there may be delays in implementation, implying that first-order conditions do not hold with equality.

The objective function of the host economy is:[39]

$$\text{(A1)} \quad W = \frac{1}{r}\left[E - \frac{1}{2}\gamma E^2 - pE_F + q(E_F * - E_F)\right] - c_F(E_F - E_{F0}) - c_1(E_R - E_{R0}) - \frac{1}{2}c_2(E_R - E_{R0})^2 .$$

E is total energy consumption in this economy:

$$\text{(A2)} \qquad E = E_F + E_R.$$

Equation (A1) represents a simple linear-quadratic welfare function related to total energy use in this economy, E_F and E_R are fossil and renewable energy consumption, assumed to be perfect substitutes, and both homogeneous.[40] Consuming one unit of E_F leads to one ton of CO_2 emissions. Consumption and production of E_R leads to no carbon emissions. p is the fossil-fuel price, and q is the ITMO price when selling and buying carbon emissions reduction credits below or beyond an initial ("baseline") amount E_F*, which corresponds to a host's unconditional Nationally Determined Contribution (NDC) toward the PA.[41] E_{R0} represents an initial (already invested)

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[39] (A1) does not allow for carbon emissions reductions due to pure energy efficiency improvements. Opening up for such improvements would expand our policy options by a further dimension, but would otherwise not fundamentally change our analysis in the following.

[40] E_F and E_R are homogeneous in the sense that they both represent the same energy for the same applications within any given period (year). We consider fossil and renewable energies to both have wide use, and there is little need to distinguish between specific uses in this (broad-based) presentation.

[41] Focusing on potential ITMO markets, in the context of Article 6.4 of the PA (a centralized trading mechanism), the ITMO market will tend toward a single *q* valid for all countries and trades. Under Article 6.2 (bilateral ITMO trading), *q* is instead likely to vary across trades and countries, and can be expected to be higher for carbon trading involving higher-income countries; see e. g. Yu et al. 2021.

amount of renewable energy supply. $E_R - E_{R0}$ represents new investments in renewable energy, representing units of energy production forever. c_R represents (fixed and constant) unit investment costs. $E_F - E_{F0}$ represents new investments in fossil-fuel based energy production capacity, where c_F is unit investment cost. This term is defined only for $E_F \geq E_{F0}$. $E_F^* - E_F$ represents ITMOs sold net by this host, which can be positive (for net ITMO sellers, mostly EMDEs/LICs), or negative (for net ITMO buyers, mostly HICs). The market price of E is determined by a zero-profit condition for the most expensive actual energy delivery. γ is a scaling constant in the host government's energy supply function.

(A1) applies to the electric power sector, but can have wider application, for example to transportation and industrial sectors. There is no time limit on selling or purchasing offsets, nor for offset crediting of investments which permanently reduce the host's carbon emissions. Renewable energy has no variable cost.[42] Energy provided by either fossil fuels or renewables is equivalent for consumers.[43]

The last square term in (A1) represents increasing marginal costs as more renewable investment projects are implemented, but can also represent adjustment or implementation costs related to increasing the energy capital stock. Renewable investments in EMDEs are typically subject to finance, capacity, technological and institutional constraints slowing investments down. Adjustments to changes in the ITMO price and other prices will then be limited, and a new equilibrium (such as the switch from fossil fuels to renewables) could in practice take time to emerge.

Maximizing (A1) with respect to E_F and E_R, we find:

(A3)
$$\frac{\partial W}{\partial E_F} = \frac{1}{r}(1 - \gamma E - p - q) - c_F \leq 0 .$$

(A4)
$$\frac{\partial W}{\partial E_R} = \frac{1}{r}(1 - \gamma E) - c_1 - c_2(E_R - E_{R0}) \leq 0 .$$

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[42] This is not strictly true, but variable costs are a small share of total costs for most renewables; see Timilsina (2020, 2021).

[43] This is not accurate: electricity from wind or PV may need to be stored. We define renewable energy amounts as adjusted for uncertain delivery times and amounts, to make units equivalent in economic value terms.

We here assume constant marginal cost c_F when expanding fossil-fuel capacity, E_F; this may be reasonable as fossil-fuel production capacity expansion will in case be small, if happening at all, and as the fossil-fuel technology is established and well-known. The solution gives potential negative inequalities for either (A3) or (A4), where at least one relation will hold with equality. In general, (A3) holds with inequality when no further investments in fossil fuel energy capacity is optimal beyond the current capacity, E_{F0}, which is then the amount of fossil fuel consumed. (A4) holds with inequality when no further renewable energy investments are optimal beyond E_{R0}.

Renewables are preferred over fossil fuels for additional energy supply given that:

$$(2.1) \qquad rc_1 < rc_F + p + q \Leftrightarrow q > r(c_1 - c_F) - p \,.$$

In this case, (A4) holds with equality, which generally determines (and endogenizes) $E_R - E_{R0} > 0$, and thus E_R.

Increased fossil-fuel energy use here requires new investments in fossil-based energy capacity. When an inequality opposite to (2.1) holds, fossil fuel capacity will be expanded, but not renewable energy capacity.

No capital costs related to fossil fuel use

Consider in this case the following (discounted) welfare measure for the host economy:

$$(A8) \qquad W = \frac{1}{r}\left[E - \frac{1}{2}\gamma E^2 - pE_F + q(H^* - E_F)\right] - c_1(E_R - E_{R0}) - \frac{1}{2}c_2(E_R - E_{R0})^2 \,.$$

Relative to (A1), the term representing fossil capital investments is now eliminated, since by assumption such investments are no longer necessary or relevant. We assume that the following two conditions hold:

$$(A9) \qquad \frac{\partial W}{\partial E_F} = \frac{1}{r}(1 - \gamma E - p - q) = 0$$

The condition for fossil fuels (equation (A9), which does not involve any additional investment) is now assumed to always be fulfilled with equality. Current fossil-fuel consumption adjusts (to changes in p and q) in the short run to make equality hold in this relation, thus endogenizing the amount of fossil fuels consumed. This feature is in turn based on an assumption that the demand for fossil fuels is limited to fossil-fuel supply based on already existing power generation capacity, and will often be less than this capacity.

For renewable energy investments, condition (A4) is still valid. With equality in (A4), it is generally optimal for the host to invest more in renewable energy, so that the solution entails $E_R > E_{R0}$. Such a case occurs when

(2.2) $$rc_1 < p + q \Leftrightarrow q > rc_1 - p\ .$$

The left-hand side of the first relation in (2.2) is the net cost per period and per unit of energy, of providing renewable energy capacity beyond E_{R0}, while the right-hand side is the net cost per unit of fossil fuels.

When the carbon price q is in the following range, (2.2) does not hold, but (2.1) holds:

(A10) $$r(c_1 - c_F) - p < q < rc_1 - p\ .$$

In such cases the host wishes to retain its fossil-fuel production capacity E_F, but not expand it further. All capacity expansion is provided by renewables.

When (2.2) holds (renewables are more productive at the margin), optimal energy consumption, given no constraint on renewable investment, is given by (A4) with equality:

(A11) $$E_R = \frac{1}{\gamma}(1 - rc_R)\ .$$

With negative inequality in (A4), optimal energy consumption is instead determined by (A9):

(A12) $$E_F = \frac{1}{\gamma}(1 - p - q)\ .$$

In both cases, optimal energy provision is decided by long-run marginal cost of energy, which in (A11) (energy supply expanded by renewables) is determined by the long-run marginal investment cost for renewables; and in (A12) (energy supply expanded by fossil fuels) by the marginal cost of fossil fuels: the fossil-fuel price p, plus the offset price q.

When $rc_R < p$, renewables are always less expensive than fossil fuels even when the carbon price is zero.

A main result from this model is that when the unit periodic capital cost for renewables, rc_R, is above (below) the level giving equality in (2.2), all energy is provided in terms of fossil fuels (renewables). This is unrealistic. In reality both fossil-fuel applications and renewables projects have unit costs on a sliding scale: higher q increases the fraction of renewable projects, and reduces fossil-fuel use. Changes in the energy system also occur gradually. With large initial fossil-fuel use only a limited part will be replaced by renewables over a given period.

The interest rate r on the periodic investment cost c_R for renewable energy, defined as the rate required to attract private investment to renewable energy projects in a given host country, can vary dramatically across countries and projects, depending on several factors including project uncertainty perceived by lenders, and interest rates in the country's credit market.

The marginal investment cost for renewable energy, c_1, is likely to be highly project and country dependent. It includes policy and administrative costs, the costs of providing the necessary technical expertise, political costs related to delays, etc. Even more important, the capital and credit costs, here represented by c_1, c_2 and r, can be (far) higher in EMDEs/LICs than in HICs and lead to lower renewable investments in the former countries. In particular, investors in LICs will often face serious credit rationing for renewable energy investments with long payback periods, and thus inability to effectuate such investments. For our model to explain how renewable investments are impacted we also need to account for expected or average delays in investment implementation, and lack of urgency of investors to take optimal action. Even for given r and c_1, (A4) may poorly capture incentives to incur renewable investments.

The carbon price plays two roles for reducing carbon emissions in this model: reducing overall energy consumption and fossil fuel use, via (A9); and (when reaching and exceeding the barrier represented by (2.2)) incentivizing the switch from fossil fuels to renewables.

Appendix B: Two-period model as basis for the analysis in section 3

We will now present a model that is slightly more elaborate than that in Appendix A, to support arguments in section 3 of the paper. We consider two ITMO trading periods, up to, and beyond, 2030. Carbon crediting is allowed for future implementation periods. ITMOs cannot be transferred between periods, referring to the ban on ITMO banking. The first period lasts for *n* years, and the second period for the remainder of time. The following formula defines (present discounted) values of the first and second period, denoted $\Phi(r,n)$ and $1-\Phi(r,n)$:

(B1) $$V(r,n)=\frac{1}{r}-\left(\left(\frac{1}{1+r}\right)^{n+1}+\left(\frac{1}{1+r}\right)^{n+2}+...\right)=\left[1-\left(\frac{1}{1+r}\right)^{n}\right]\frac{1}{r}=\Phi(r,n)\frac{1}{r}.$$

$\Phi(r,n)$ represents the relative (discounted) value of the first PA implementation period. Schematically and for simplicity, the second period has infinite length.

Assume that sufficient production capacity exists for the use of fossil fuels, so that no new energy investments are made in fossil-based infrastructure, not even in period 1. The key issue is whether and to what degree the host will *scale down* its fossil fuel consumption, in each of the two periods. This is assumed to hold regardless of the values of the carbon (ITMO) prices in the two periods, q_1 and q_2; thus even when q_1 is "low". We will generally assume that $q_2 > q_1$, based on the argument that q_1 is "low", and that there is a scaled-up effort to reach the NZE by (around) 2050.

The host in question has the following preference function:

(B2)

$$W=\frac{1}{r}\left[\Phi[E_1-\frac{1}{2}\gamma E_1^{2}-p_1E_{F1}+q_1(E_{F0}-E_{F1})]+(1-\Phi)[E_2-\frac{1}{2}\gamma E_2^{2}-p_2E_{F2}+q_2(E_{F1}-E_{F2})]\right]$$
$$-c_{11}(E_{R1}-E_{R0})-\frac{1}{2}c_{12}(E_{R1}-E_{R0})^2-(1-\Phi)[c_{21}(E_{R2}-E_{R1})+\frac{1}{2}c_{22}(E_{R2}-E_{R1})^2].$$

Subscripts 1 and 2 represent the two periods; otherwise, variables are the same as in Appendix A. The first line in (B2) represents energy supply and variable (fossil fuel) inputs. We assume that the baseline against which to claim carbon market revenues is updated, so that GHG emissions in period 1 are the baseline for period 2. As already mentioned, no investments are made in fossil fuel-based energy capacity, as fossil-fuel consumption is being scaled down. The second line represents the costs of additional renewable energy investments in each of the two periods, which are both linear-quadratic functions. Energy investments in period 1 last through period 2. The square terms represent a combination of declining efficiency of additional renewable energy investments, and "adjustment costs" when making such investments, due to a range of potential factors: sluggishness in the process of renewables investments to long-term optimal levels; imperfections in the host's credit and capital market required for these investments; and technical and political issues related to implementing such investments for EMDE/LIC hosts. Our specification leads, for all relevant parameter configurations, to a solution where renewable energy investments are positive in both periods. Note also that, formally in (B2), period 2 is "open" and does not "end" in 2050.

The country's energy consumption levels in the two periods are

(B3) $$E_1 = E_{F1} + E_{R1}$$

(B4) $$E_2 = E_{F2} + E_{R2}.$$

q_1 and q_2 are expected (average) ITMO prices in the two periods. Carbon crediting of renewable investment projects is allowed also after 2030.

For simplicity and to focus on this set of cases, we assume that all first-order conditions are fulfilled with equality.[44] The first-order conditions determining the host's energy consumption (fossils plus renewables) in periods 1 and 2 are:

(B5) $$\frac{\partial W}{\partial E_{F1}} = \frac{\Phi}{r}(1-\gamma E_1 - p_1 - q_1) + \frac{1-\Phi}{r} q_2 = 0$$

(B6) $$\frac{\partial W}{\partial E_{F2}} = \frac{1-\Phi}{r}(1-\gamma E_2 - p_2 - q_2) = 0\,.$$

These relations solve for the host's total energy consumption in each of the two periods:

(B7) $$E_1 = \frac{1 - p_1 - q_1 + \frac{1-\Phi}{\Phi} q_2}{\gamma}$$

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[44] This differs from the solutions derived in section 2, on the basis of a one-period model that is otherwise very similar to the current model, but where a main objective was to study border cases where inequalities could appear. The objective in this section is rather to focus on internal solutions, with equalities holding in all relations.

(B8) $$E_2 = \frac{1 - p_2 - q_2}{\gamma} .$$

Optimal renewable energy investments in the two periods are found by taking derivatives in (B2):

(B9) $$\frac{\partial W}{\partial E_{R1}} = \frac{\Phi}{r}(1 - \gamma E_1) - c_{11} - c_{12}(E_{R1} - E_{R0}) + (1 - \Phi)\left[c_{21} + c_{22}(E_{R2} - E_{R1})\right] = 0 .$$

(B10) $$\frac{\partial W}{\partial E_{R2}} = (1 - \Phi)\left[\frac{1 - \gamma E_2}{r} - c_{21} - c_{22}(E_{R2} - E_{R1})\right] = 0 .$$

From (B8):

(B11) $$E_2 = \frac{1 - r[c_{21} + c_{22}(E_{R2} - E_{R1})]}{\gamma} .$$

We assume that $E_2 > E_1$; both these variables can be considered as determined from (B7) - (B8).[45] This means that (B9) and (B10) determine E_{R1} and E_{R2}, found by inserting for E_1 and E_2 from (B5) - (B6) in (B7) - (B8). We see that q_1 and q_2 do not enter into (B9) - (B10). Changes in the q_i variables (i = 1,2) directly impact on E_{F1} and E_{F2} in (B7) - (B8).

We find from (B7) and (B9):

(B12) $$E_{R1} = E_{R0} + \frac{1}{c_{12}}\left(\frac{1}{r}[\Phi(p_1 + q_1) + (1 - \Phi)p_2] - c_{11}\right) .$$

From (B10) and (B12) we find:

(B13) $$E_{R2} = E_{R0} + \frac{1}{c_{22}}\left(\frac{p_2 + q_2}{r} - c_{21}\right) + \frac{1}{c_{12}}\left(\frac{1}{r}[\Phi(p_1 + q_1) + (1 - \Phi)p_2 - c_{11}\right) .$$

From (B12) and (B13) we find the following partial derivatives:

(B14) –(B15) $$\frac{dE_{R1}}{dq_1} = \frac{dE_{R2}}{dq_1} = \frac{1}{c_{12}}\frac{\Phi}{r}$$

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[45] Technically, from (B5) - (B6), if the carbon price in period 2 is higher ($q_2 > q_1$), $p_1 > p_2$ by a wider margin is needed. Overall energy demand is likely to be higher in period 2, due to economic growth, and technological progress in the renewable investment sector, not represented here.

(B16) $$\frac{dE_{R1}}{dq_2}=0$$

(B17) $$\frac{dE_{R2}}{dq_2}=\frac{1}{c_{22}}\frac{1}{r}.$$

These results show that q_1 impacts positively, and identically, on E_{R1} and E_{R2}, while q_2 impacts (also positively) on only E_{R2}. Note also that for hosts facing high *r* (typically, L countries), Φ will tend to be large and 1-Φ small. A low level of q_1 will for such hosts have a (too) small positive impact on first-period renewable energy investments, E_{R1}. An implication is that for most L countries, even when the future expected value of q_2 is high, q_1 will be the dominant factor in determining E_{R1}. A low value of q_1, expected for early trading under the PA, is then likely to hold back early renewable energy investments in EMDE/LIC countries. From (B15), this also holds back the accumulation of renewable energy investments in the second period; there is here no later "catching-up" following an initial renewable investment slowdown.

Fossil fuel consumption in the two periods is residually determined from (B7) - (B8), and (B12) – (B13). We find the following impacts of carbon prices in the two periods on fossil-fuel consumption and carbon emissions:

(B18) $$\frac{dE_{F1}}{dq_1}=-\frac{1}{\gamma}-\frac{1}{c_{12}}\frac{\Phi}{r}$$

(B19) $$\frac{dE_{F2}}{dq_1}=-\frac{1}{c_{12}}\frac{\Phi}{r}$$

(B20) $$\frac{dE_{F1}}{dq_2}=\frac{1}{\gamma}\frac{1-\Phi}{\Phi}$$

(B21) $$\frac{dE_{F2}}{dq_2}=-\frac{1}{\gamma}-\frac{1}{c_{22}}\frac{1}{r}.$$

Carbon prices in the two periods impact on fossil-fuel consumption and thus on carbon emissions. The direct impacts of carbon pricing on carbon emissions in the same period are negative, as expected, and composed of two elements: one direct element reducing the host's overall energy consumption; and an element stemming from increased renewable energy consumption (which "leaves room for" less fossil-fuel-based energy). Note that the last elements on the right-hand sides of (B18), (B19) and (B21) are the negatives of the impacts on E_{R1} and E_{R2} from (B14), (B15) and (B17).

We also find that fossil energy consumption in period 2 falls when q_1 increases. The reason for this is that renewable energy use in period 2 then increases (as a "knock-on" effect of an increase in E_{R1} which "automatically" increases E_{R2}), also here leaving less room for fossil energy use. The most interesting impact is perhaps that of q_2 on fossil-fuel consumption and carbon emissions in period 1, which is positive. The reason is different from that for the other effects. In this case, carbon trading in period 2 becomes more attractive to the host when the period 2 quota price is higher. Since the carbon emission level in period 1 is assumed to be the baseline against which reduced emissions can be traded in period 2, a higher GHG emission level in period 1 makes room for a greater emission reduction, and more sales of carbon assets, in period 2. A high expected carbon price in period 2 induces the host to retain much of its fossil fuel consumption, and hold back on its transition to renewable energy use, in order to gain by selling more carbon assets later.

Appendix C: Additional cases in section 4

Case 1

ITMO market not available, constrained compensation mechanism

The host's NDC mitigation target is, in case 1 of section 4, required to be upscaled at the same rate as the ER induced by the donor-sponsored carbon tax. The ITMO market is here not (yet) available, so that the element $q(H_0 - E_F)$ drops out of (4.1) and (4.3). The carbon price in the host economy is then the donor-supported carbon tax, t.

In this alternative case, we assume that the host is compensated for its deadweight loss (DWL) from implementing the domestic carbon tax, according to formula (4.2). The donor's own gain function is

$$\text{(C1)} \qquad V_D = (v-t)(E_0 - E_F) = (v-t)At\,.$$

Maximizing (4.10) with respect to t, we find

(C2) $$\frac{dV_D}{dt} = (v - 2t)A = 0 \Leftrightarrow t_1 = \frac{v}{2}.$$

t_1 is the constrained optimal t from the point of view of the donor in this case. This tax is only half of the donor's marginal carbon value; and half of the level in (4.12). In our model, the ER implemented by this tax, and the corresponding upscaling of the host's NDC target, is only half of the level found in subsection 4.3.

Compensation for the DWL is here the only compensation required for the host. Under the specified mechanism, however, the host will be over-compensated for this loss.

The donor is in this case assumed to not be able to extract the producer surplus directly from the host economy, but instead needs to set its preferable tax support rate, t_1, given that (4.2) is used to compensate the host for its allocation loss.

ITMO market available, optimal compensation mechanism

We will now (and for the next case) assume that the ITMO market is available to hosts when the donor support is offered. This means that carbon emissions in the host economy, before being offered RBCF support, are given by (4.4) with $q > 0$, being optimally adapted to the ITMO market.

The total carbon price in the host economy is $q + t$.

We first assume that the total compensation to the host is the DWL (the Harberger triangle) related to implementing the carbon tax, plus the compensation for inability to sell ITMOs; as the host is now already optimally adapted to the ITMO price q. We find $\partial V_G/\partial E_F = q + t$ (from (4.1) and (4.4)). The donor's own gain function is its gross gain, $v(E_{F0} - E_F)$ (which equals the value to the donor of the mitigation implemented on the basis of the imposed tax t), minus the minimum compensation the host needs to implement this mitigation. This difference equals:

(C3) $$V_D = v(E_0 - E_F) - \frac{1}{2}t(E_0 - E_F) - q(E_0 - E_F) = \left(v - q - \frac{1}{2}t\right)At = (v-q)At - \frac{At^2}{2}.$$

v is the donor's social cost of carbon, and E_{F0} is the host's carbon emissions before t is imposed. v-q can be interpreted as a "net value" of mitigation for the donor: the donor's total carbon value, minus what the market already provides in terms of value.

Maximizing (C3) with respect to t gives:

$$\text{(C4)} \qquad \frac{dV_D}{dt} = (v - q - t)A = 0 \Leftrightarrow t_1 = v - q \, .$$

t_1 is the optimal t from the point of view of the donor. This tax is now adjusted down from the "standard" level, v, to the net value identified above, by subtracting the ITMO price, q. The total carbon price facing the host economy is v, which comprises two components: the ITMO price, q; and the domestic carbon tax supported by the donor, v-q.

The host here needs two types of support to implement t_1: compensation for the DWL; and compensation for foregone ITMO revenue, $q(E_{F0} - E_F)$. While the latter compensation is not allowed under current rules, it is necessary for incentivizing this policy change by the host.

ITMO market available, constrained compensation mechanism

The host is here compensated for its DWL from implementing the domestic carbon tax by formula (4.2). We still find $\partial V_G/\partial E_F = q + t$ (from (4.1) and (4.4)). The donor will now need to supply $q+t$ per unit of mitigation induced, to ensure that the host has incentives to set the donor's desired carbon tax. The donor's own gain function is

$$\text{(C5)} \qquad V_D = (v - q - t)(E_0 - E_F) = (v - q - t)At \, .$$

Maximizing (C5) with respect to t yields

$$\text{(C6)} \qquad \frac{dV_D}{dt} = -tA + (v - q - t)A = 0 \Leftrightarrow t_1 = \frac{v - q}{2} \, .$$

t_1 from (C6) is now the constrained optimal t from the point of view of the donor.

The donor is here assumed to not be able to extract the producer surplus directly from the host economy, but instead sets its preferable tax support rate, t_1, given the compensation rule (4.2). This tax, from (C6), is only half of its optimal value, from (C4). q here represents the opportunity value for the host, related to not accepting the carbon tax subsidy.

Case 2

Donor assistance to the host for reaching its NDC target

In case 2, the host country has not yet reached its (unconditional) NDC target and needs to reduce its GHG emissions to reach that target. The host can reach this target by imposing a comprehensive domestic carbon tax t^*. Assume that the host government's true acceptance to impose its own domestic carbon tax is limited to a lower level, $t_G < t^*$. The donor recognizes that, out of a carbon tax t imposed in the host country, the host itself is willing to cover a share t_G, while the donor covers the rest. We assume that the ITMO market already exists, so that the host has already adapted its mitigation level optimally to the ITMO price q.

The host is also in this case not allowed to sell ITMOs in the carbon market; this here holds for units mitigated up to its (unconditional) NDC target level, which is the case we consider.

Consider possible donor support to a comprehensive carbon tax up to t^* required for the host to implement its unconditional NDC target.

Constrained compensation mechanism

When the efficient solution cannot be implemented, and a compensation rule for DWL takes the form (4.2), the donor's objective function is:

(C7) $$V_D = (v - q - t + t_G)tA .$$

We focus on the case where the donor provides the host government a constant support to implement a carbon tax. The donor's first-order condition yields (given that $t_2 \leq t^*$)

(C8) $$\frac{dV_D}{dt} = -tA + (v - q - t + t_G)A = 0 \Leftrightarrow t_2 = \frac{v - q + t_G}{2} .$$

The total carbon tax imposed in the host economy (up to the level t^*) is here t_2, while the support paid by the donor to the host per unit of mitigation is

(C9) $$t_2 - t_G = \frac{v - q - t_G}{2} .$$

As already discussed in subsection 4.3, we also here need to distinguish between three cases.

If $t_2 < t^*$, this donor support is not sufficient for the host to reach its NDC target. Additional policies are then needed for the host to reach this target.

If $t_2 = t^*$, the donor's optimal support policy is exactly sufficient for the host to reach its NDC target.

If $t_2 > t^*$, the NDC target will be over-reached so that the host can sell a net volume of ITMOs in the Article 6 carbon market. The exact solution for the implemented carbon tax is then not given by (4.15) but can be either higher or lower than this level.

The total carbon price in the host economy will here be $t_i + q$, for $i = 1 - 3$. Thus, in particular for the present case, the total carbon price in the host economy, τ_2, is then

$$\tau_2 = \frac{v - q + t_G}{2} + q = \frac{v + q + t_G}{2}. \tag{C10}$$

This total carbon price is most likely below v, but not necessarily much less; we find similar results in cases 1 and 3.

Case 3

Support to carbon taxation without target upscaling

Efficient compensation mechanism

A "case 3" is included for completeness and as it is of interest for our overall analysis. The host has here already fulfilled its NDC target and intends to accomplish additional ER for selling in the ITMO market. This case is not included in the discussion in section 4, as it formally conflicts with current Article 6 rules, which prescribe that when ER resulting from RBCF support is sold in the carbon market, this support must be reimbursed to the donor. We will also study what such a reimbursement rule can mean for host incentives.

Another difference between this case and cases 1-2 is that now the supply of ITMOs to the market increases as a result of the RBCF support from donors, which can impact on global mitigation.[46]

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[46] When new mitigation is incentivized beyond the host's NDC target, the resulting carbon credits will be sold in the ITMO market. The net increase in global mitigation will then depend on the slopes of the global supply and demand functions for ITMOs, but will generally be less than the primary increase in ITMO supply; thus $\beta < 1$. Note that

The host's emission level is now, before receiving donor support, already optimized with respect to the host's ITMO market access. This means that the condition for the starting emissions level of the host, given by (C4), now contains the term q, which it did not in cases 1-2. The starting emission level is thus lower, and the host needs donor support to be willing to reduce its GHG emissions to even lower levels.

We consider two cases: first, the efficient case where the host's DWL is exactly compensated, and secondly, an inefficient case where RBCF is provided according to (4.2).

The donor's net gain from support to carbon tax implementation in the host country is:

(C11)
$$V_D = \beta v A t - \frac{1}{2} A t^2 .$$

The necessary compensation to the host for imposing the carbon tax t is now the Harberger triangle represented by the last term in (C11). β is the fraction of the ER, incentivized in the host economy, realized globally, and not lost to "leakage" via a reduced international ITMO price when more ITMOs are supplied internationally. The RBCF support from the donor to the host then equals the host's reduced carbon tax receipts from domestic mitigation due to implementing the carbon tax t. In (C11) there is no deduction for foregone ITMO revenues (which occurred in cases 1-2) as these revenues are now being retained by the host.

The donor selects its optimal t, now called t_3, by maximizing (C11) with respect to t, yielding (with the last equality derived in the same way as under the two former cases)

(C12)
$$\frac{dV_D}{dt} = (\beta v - t)A = 0 \Leftrightarrow t_3 = \beta v .$$

Importantly the host still needs support from the donor to implement this ER, even though the host gains from selling the generated ER as ITMOs in the market. The host still also needs compensation for its DWL when implementing the carbon tax t_3.

The total carbon price in the host economy is now $\beta v + q$, which can be greater or lower than v depending on the leakage rate 1-β.

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when all countries exactly fulfill their NDCs, and all NDCs are kept unaltered, "leakage" will be complete (so that $\beta = 0$) as no mitigation is induced at the global level.

There is here a need for climate finance support by donors to the host country, as the host country's ER is beyond what would be chosen with no donor support. But RBCF support is not allowed under current Article 6 rules in this case. This case can still be relevant in future cases with an ITMO market that is open to all host and mitigation options. RBCF support is here still required for the host to implement the carbon tax, even when the resulting ER is sold in the ITMO market. The Article 6 rules which govern this case may here need to be revisited.

Constrained compensation mechanism

We now assume that the donor uses formula (4.2) to compensate the host's DWL. The donor's gain from support to the host's carbon tax implementation is:

(C12) $$V_D = (\beta v - t)tA \,.$$

The donor now selects its optimal value of *t* by maximizing (B12) with respect to *t*, yielding

(C13) $$\frac{dV_D}{dt} = -tA + (\beta v - t)A = 0 \Leftrightarrow t_3 = \frac{\beta v}{2} \,.$$

The host still needs support from the donor to implement this ER, as it still bears a DWL that needs compensation, even though the host now gets full compensation for selling the resulting ITMOs.

Overall evaluation of the alternatives studied

When compensation to hosts for implemented ER can be targeted to the exact DWL, the donor is willing to support a carbon tax in the host country equal to the donor's own value of carbon. In case 3 this is different: the donor is then uncertain about the global mitigation impact of a carbon tax implemented in one particular host country, due to possible leakage.

In all cases 1-3, donor support depends on whether the host's DWL is exactly replaced, or over-compensated. There are several possible reasons why compensation to the host will need to go beyond the exact DWL. Asymmetric information can make this solution problematic. The donor must know the relationship between carbon pricing and mitigation in the host economy; and must also know what level(s) of carbon taxes the host is ready to accept. If not, the donor may be constrained to offer support contracts of less efficient types. Formula (4.2) is an example of such a constrained support function. Strong political resistance to domestic carbon taxes could also make a robust carbon tax difficult to implement for the host government. High political costs could make such a policy change "expensive" for the host. It may be expensive to compensate the actors in the host country sufficiently to actually implement the required carbon tax. There may be strong resistance to the fuel price increases that follow from a new carbon tax, among consumers and producers. This effect might be offset or lessened through reallocations of the government's increased carbon tax revenues, but such policies are often not carried out, nor well understood among the public and thus problematic politically. Resistance could be most serious early. Once a host country gets "used to" a carbon tax (implemented in many similar countries), and the host's fossil fuel consumption is reduced because of the tax (and renewable energy consumption increased), the tax can become more accepted. Such a rationale could potentially explain why it can be a useful (if necessary) to return the provided RBCF funds "later", after the carbon tax has been implemented, and hopefully accepted by the public.

A factor working in the opposite direction is co-benefits for the host from mitigation induced by a national carbon tax (for example, via reduced air pollution). Such factors could make the host government more interested in implementing the carbon tax hike. So far, however, we have never or rarely seen such preferences being displayed by host countries in EMDEs/LICs.

Appendix D: Simple model of NZE solution by 2050 when NET alternatives are included

In this appendix we present a model, similar to that in section 2, to illustrate the nature of an NZE by 2050 (or somewhat later), given that it is sought and reached. We discuss some key aspects of such a solution: what drives it, how overall GHG mitigation is implemented in different world regions; and implications of an NZE for implementation costs and the distribution of costs and net revenues across countries. We explicitly model NETs, their costs, and roles.

For this purpose, in the simplest way possible, we add a module describing NET activity and impacts, providing the option to sequester carbon independently of energy use. We distinguish between two main global regions: region 1 (HICs), and region 2 ("rest of the world"). For each region we add a (linear-quadratic) sequestration function $S_i(E_{Hi})$, which shows the costs of sequestering an amount E_{Hi} of carbon annually in region i = 1, 2. The most relevant NET technologies for carbon sequestration are, in region 1, DAC and BECCS. In region 2 we assume that NBS alternatives will be most significant, mainly afforestation and reforestation, and SCS.

Define the sequestration cost functions for the two regions by

(D1) $$S_1(E_{H1}) = aE_{H1} + \frac{1}{2}\lambda E_{H1}{}^2$$

(D2) $$S_2(E_{H2}) = bE_{H2} + \frac{1}{2}\beta E_{H2}{}^2.$$

For both regions, the optimal sequestration cost functions are quadratic with rising marginal costs, assuming that the cheapest alternatives will be utilized first. Schematically, we can identify low a or b coefficients with the costs of the cheapest NETs being available to region 1 and 2; while low λ or β coefficients indicate plentiful availability of NET options at cost levels similar to those of the least expensive alternatives.

E_H denotes the flow of total sequestered carbon:

(D3) $$E_H = E_{H1} + E_{H2}.$$

Define total global GHG emissions "near the end point" by H. A net-zero solution by 2050 requires that $H = 0$ at that point. This gives the following basic relationships:

(D4) - (D5) $$H = E_F - E_H = H_1 + H_2 = 0.$$

H_i denotes total net GHG emissions from region i. The requirement that net emissions be zero in 2050 does not imply that all countries or regions need to have zero GHG emissions when there is access to NETs. The requirement is that when some countries or regions have positive net GHG emissions (including NET utilization), other regions need to have negative net emissions. When region i (= 1, 2) has positive emissions, the other region needs to have negative net emissions. Net emissions from region i are

(D6) $$H_i = E_{Fi} - E_{Hi}, i = 1, 2.$$

From (D5), $H_1 + H_2 = 0$. Consider an optimal allocation of energy resources and carbon emissions around the point when net global GHG emissions are assumed to reach net-zero (perhaps around 2050). Fossil fuels are assumed to still have a place in global energy supply, although for different purposes from those of renewables which are likely to dominate electric power generation at that point, and such that no new fossil-fuel capacity is needed.[47] Additional capacity for renewables-based electric power generation is however still needed. We can on this basis specify separate welfare relationships for fossil fuels and renewable energy. The (generic) periodic welfare function of a given party (here world region, with $i = 1, 2$) could then have the following specification (focusing on a high-income country):[48]

(D7)

$$V_i = E_{Fi} - \frac{1}{2}\gamma_{Fi} E_{Fi}{}^2 - pE_{Fi} + E_{Ri} - \frac{1}{2}\gamma_{Ri} E_{Ri}{}^2 + q(H_i * - E_{Fi} + E_{Hi}) - rc_{Ri}(E_{Ri} - E_{R0i}) - aE_{Hi} - \frac{1}{2}\lambda E_{Hi}{}^2 .$$

H_i* is defined as the GHG emissions target for world region i by 2050. Assuming that an NZE solution is both targeted and implemented in 2050, the aggregate target, $H*$, will be zero, so that $H_1* + H_2* = 0$. This means that, generally, one region will set a positive GHG emissions target for 2050, while the other region will set an equally negative target. Reasonably, region 1 will set the negative target, while region 2 will set a positive target. An issue which is still unclear is which region is likely to have positive, and negative, net carbon trading revenues, $q(H_i* - H_i)$.

Assume that a given and unitary carbon price q, facing all parties and agents in both regions, clears the global carbon market, and that all take q as exogenously given. We can then view V_i as maximized with respect to E_{Fi}, E_{Ri} and E_{Hi}, taking q as given, which yields (for $i = 1, 2$):

(D8) - (D9)

$$\frac{\partial V}{\partial E_{Fi}} = 1 - \gamma_F E_{Fi} - p - q = 0$$

(D10) - (D11)

$$\frac{\partial V}{\partial E_{Ri}} = 1 - \gamma_{Ri} E_{Ri} - c_{Ri} = 0$$

(D12)

$$\frac{\partial V}{\partial E_{H1}} = q - a - \lambda E_{H1} = 0$$

(D13)

$$\frac{\partial V}{\partial E_{H2}} = q - a - \lambda E_{H2} = 0 .$$

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[47] Applications where fossil-fuel based energy could still be cost competitive and relevant are certain industrial processes, and long-haul transport such as aviation and shipping.

[48] We specify this function on a periodic instead of discounted basis, but its fundamentals are otherwise the same as for (1).

We derive the following solutions for the endogenous variables:

(D14) - (D15)
$$E_{Fi} = \frac{1-p-q}{\gamma_{Fi}}, i = 1, 2$$

(D16) - (D17)
$$E_{Ri} = \frac{1-rc_{Ri}}{\gamma_{Ri}}, i = 1, 2$$

(D18) - (D19)
$$E_{H1} = \frac{q-a}{\lambda}; E_{H2} = \frac{q-b}{\beta}.$$

(This solution requires $q \geq \max\{a, b\}$; if not, at least one region does not have incentives to apply NET technologies.) Fossil-fuel consumption in both regions is here impacted negatively by the carbon price, while CCS is impacted positively. The amount of renewables supply, E_{Ri}, is not impacted by the carbon price, but only by the supply factors for this sector. The reason is that fossil fuels and renewables are here "compartmentalized" so that increased renewables use does not impact on fossil fuel demand.[49] We assume that, by 2050 (or somewhat later), the basic substitution of renewables for fossil fuels, as part of the global transition to NZE, has been fully accomplished. Each of the two fuels then has its own separate steady-state application. More generally, the CCS activity does not impact on energy supply except through the carbon price q, which is considered exogenous. The carbon price can in principle induce an NZE without CCS, but this will require a complete strangulation of fossil-fuel supply.[50] (It also requires a very high carbon price, $q = 1-p$, which will drain the entire private social surplus from production.)[51]

We find the following solutions for the H_i:

(D20)
$$H_1 = \frac{1-p-q}{\gamma_{F1}} - \frac{q-a}{\lambda}$$

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[49] Note that renewable supply independent of the carbon price was also found in the model of section 2, in the cases where either only fossil fuels are chosen, or only renewables are chosen.

[50] We here ignore other GHGs. While emissions of methane can be reduced substantially, it can probably never be fully eliminated. The consequence is that when not being able to resort to CCUS, a global NZE probably cannot be reached.

[51] Note however that our linear-quadratic utility functions in fossil fuels are likely to be good approximations only in cases with relatively small variable changes, and not necessarily in extreme cases such as with complete phase-out of fossil fuels discussed here.

(D21) $$H_2 = \frac{1-p-q}{\gamma_{F2}} - \frac{q-b}{\beta}.$$

Focusing on the case of a unified carbon market with a single common carbon price, the market is cleared, under the net-zero condition for global GHG emissions, $H = 0$, by the common quota price $q = q^*$. Using (5.20) - (5.21),

(D22) $$\left(\frac{1}{\gamma_{F1}} + \frac{1}{\gamma_{F2}} + \frac{1}{\lambda} + \frac{1}{\beta}\right) q^* = \left(\frac{1}{\gamma_{F1}} + \frac{1}{\gamma_{F2}}\right)(1-p) + \left(\frac{a}{\lambda} + \frac{b}{\beta}\right).$$

The solution for q^* from (D22) can then be inserted into equations (D20)-(D21) to derive the actual (negative or positive) emission rates for the two regions.

We can also compute the net flow of revenues from carbon trading between the two regions, R_i:

(D23) - (D24) $$R_i = (H_i^* - H_i)q^*, i = 1, 2.$$

Here $R_1 = -R_2$ by definition.

Net carbon trading revenues for a given region will depend on the region’s emission target relative to its emission rate. Thus, if region 1’s GHG emission rate, H_1, is negative, its target rate, H_1^*, must be even greater negative for region 1 to have negative, and region 2 positive, net carbon trading revenues.

Some generalizations of this simple model are straightforward. One is to allow for differing (average) carbon prices q in the different regions. Reasonably, the HIC region will then have the highest average carbon price. Individual countries or regions may also impodr domestic carbon taxes t, as discussed in section 4 above, implying that their total carbon price will be $q + t$.

Differing total average carbon prices in different regions will result in global inefficiencies which can be evaluated. For further analysis of carbon pricing principles involving both GHG emissions and removal, see Franks et al. 2023, and Lemoine 2023.

Adjustments should also be made for CCS solutions that are non-permanent, such as most of the NBS solutions considered in section 5; see Edenhofer et al. 2023, and Kalkuhl et al. 2022.

List of acronyms

AMC = Advance Market Commitment

AUM = assets under management

BAU = business-as-usual

BECCS = bioenergy with carbon capture and storage

CA = corresponding adjustment (for ITMOs under the PA)

CCS = carbon capture and storage

CCUS = carbon capture, utilization and storage

CO_2 = carbon dioxide

CO_2e = carbon dioxide equivalent

CPI = Climate Policy Initiative

DAC = direct air capture

DWL = deadweight loss

EJ = Exajoule (10^{18} joules ≈ 278 TWh)

EMDE = Emerging markets and developing economy (country group)

EOR = enhanced oil recovery

ER = emission reduction

EU ETS = European Union Emissions Trading Scheme

EV = electric vehicle

EW = enhanced weathering

GCF = Green Climate Fund

GHG = greenhouse gas

GT = gigaton

HIC = high-income country (country group)

HT DAC = high-temperature aqueous direct air capture

ICE = internal combustion engine (for motor vehicles)

IEA = International Energy Agency

IFC = International Finance Corporation (part of the World Bank Group)

IFI = International Financial Institution

IMF = International Monetary Fund

IPCC = Inter-governmental Panel on Climate Change

ITMO = Internationally Transferrable Mitigation Outcome

kWh = kilowatt hour

LIC = lowest-income country (country group)

LT DAC = low-temperature solid-sorbent direct air capture

LTS = long-term strategy

MDB = Multilateral Development Bank

NBS = nature-based solution

NDC = nationally determined contribution (by a party to the PA)

NET = negative emissions technology

NZE = Net Zero Emissions (by 2050 Scenario)

PA = Paris Agreement

PV = photo voltaics (solar-cell technologies)

SCS = soil carbon sequestration

TWh = terawatt hour (= 10^{12} watt hours = 10^{9} kWh)

UNEP = United Nations Environment Programme

UNFCCC = United Nations Framework Convention on Climate Change

WB = World Bank

WBG = World Bank Group