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The Net Emissions Impact of HFC-23 Offset Projects from the Clean Development Mechanism

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RESOURCES FOR THE FUTURE

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Abstract

Ideally, carbon offset programs issue each project a number of offset credits equal to the number of reductions in carbon emissions it achieves. Realistically, any one project likely receives more or less offset credits than the emissions it reduces. Therefore, the net emissions impact of offset programs depends on the relative magnitude of over- and under-crediting. We apply a theoretical framework that differentiates between credited offsets and realized emissions reductions to quantify the net emissions impact of hydrofluorocarbon-23 (HFC-23) projects, which have traditionally dominated the supply of credits within the Clean Development Mechanism (CDM). In our analysis, we account for perverse incentives created by CDM methodologies and for conservative aspects of CDM methodologies. We find it likely that under-credited emissions reductions nearly equal the supply of over-credited offsets, implying that CDM HFC-23 projects effectively have little impact on net emissions and thereby maintain their environmental integrity, on average. Ignoring the supply of under-credited emissions in the context of CDM HFC-23 projects therefore exaggerates the influence of perverse incentives created by CDM methodologies that lead to over-credited offsets.

Key Words: carbon offsets, China, environmental accounting, cap and trade, policy instruments and evaluation, climate policy, Clean Development Mechanism

JEL Classification Numbers: D01, Q54, Q56

Contents

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1. Introduction

About 40 national and 20 subnational jurisdictions currently price ~6 $GtCO_2e$ of greenhouse gas (GHG) emissions, equivalent to roughly 12 percent of annual GHG emissions (World Bank and Ecofys 2014). These programs typically regulate a portion of the economy and leave the remaining sectors uncovered. These uncovered sectors—which usually include the agricultural and forestry sectors, as well as emitters of potent GHGs—can usually supply a large amount of carbon mitigation at low costs relative to covered emitters (Fischer 2005; Murray, Sohngen, and Ross 2006; Fell et al. 2012; van Benthem and Kerr 2013). Many carbon pricing programs therefore contain carbon offsetting methodologies that allow uncovered emitters to reduce carbon emissions and receive a credit in return.[1] Covered emitters can then purchase these credits and use them to comply with the carbon price.

Regulators generally expect one credit to reduce one ton of carbon emissions because allowances typically represent the right to emit one ton of carbon emissions, and offsets and allowances are presumed to be perfect environmental substitutes.[2] The environmental integrity of carbon offsets therefore critically depends on the net emissions impacts of projects credited within these markets. Ideally, carbon offsetting methodologies issue each project a number of offset credits at least equal to the number of reductions in carbon emissions it achieves. Realistically, any one project likely receives more or less offset credits than the emissions it reduces, which would increase or decrease, respectively, the effective cap if used in a cap-and-trade system.

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[1] In practice, virtually all cap-and-trade policies contain offset provisions while carbon tax policies rarely include offset provisions.

[2] The terminology of "allowances" pertains to cap-and-trade policies, but one might equivalently imagine that an offset could be used as a substitute for a carbon tax obligation that covers one ton of carbon emissions.

The Kyoto Protocol (KP) created the largest carbon offsets market in the world, the Clean Development Mechanism (CDM), which allows projects in developing countries to sell credits to polluters in developed countries for satisfying compliance obligations imposed by carbon pricing programs (United Nations 1998).[3] Since starting in 2006, the CDM has awarded one-third of its credits to a particular class of carbon offsets: projects that virtually eliminate hydrofluorocarbon-23 (HFC-23) emissions from facilities that produce chlorodifluoromethane (HCFC-22) (Fehnann 2015). In our analysis, we provide quantifications that comprehensively and empirically address whether CDM regulators issued a number of offset credits (which the CDM terms "certified emissions reductions," or "CERs") greater or less than the amount of emissions reduced by 12 HFC-23 projects in China and Mexico between 2006 and 2013.

Previous work has documented that CDM rules led to awarding HFC-23 projects with more CERs than warranted by the emissions reductions they achieved, calling into question the environmental integrity of the CDM (Wara 2008; Schneider 2011). The literature identifies at least two forms of perverse incentives leading to over-crediting in offsets markets: moral hazard, where rules give an incentive to artificially inflate emissions; and adverse selection, where rules incentivize projects that already have low emissions to participate in the offset market (Bushnell 2012; Millard-Ball 2013). The policy literature finds significant evidence that CDM rules for HFC-23 projects create moral hazard (Wara 2008) and adverse selection (Schneider 2011), which leads to over-crediting (Cullenward and Wara 2014).[4]

Certain CDM rules, however, may lead to significant under-crediting, where projects receive fewer credits than their actual emissions reductions. To the best of our knowledge, no study has empirically evaluated the extent of under-crediting from a major source of offset credits and compared the magnitude of over-crediting and under-crediting, despite a growing literature that emphasizes its importance (Schneider 2009; Bushnell 2012; Bento et al. 2012; van Benthem and Kerr 2013) and acknowledges that under-crediting counterbalances and can even dominate emissions increases from over-crediting—leading to net reductions, rather than increases, in emissions via offset use (Warnecke 2014; Bento et al. 2015). The CDM rules that

[3] In this context, "polluters" can be governments in developed countries that purchase credits for their commitments under the Kyoto Protocol, or firms that acquire credits and submit them for compliance with a cap-and-trade or carbon tax policy operated by their government.

[4] Schneider and Kollmuss (2015) investigate perverse incentives at two HFC-23 projects in Russian under the Joint Implementation program, which used methodologies that differ significantly from those used in the CDM.

governed the issuing of CERs to HFC-23 projects, moreover, contain conservative parameters and methodologies that led to some degree of under-crediting.[5] We therefore view a complete accounting of over- and under-crediting as crucial to understanding the environmental integrity of CDM HFC-23 projects and as a prerequisite to informed policy decisions.

In Section 2, we present a conceptual framework that accounts for perverse incentives and baseline-setting designs to illustrate the net emissions impacts of offset programs. In Section 3, we elaborate on the causes of over-credited offsets and under-credited emissions reductions in the specific context of HFC-23 projects. Section 4 describes our empirical modeling approach, and Section 5 details the results. In Section 6, we provide a brief discussion of our results, and Section 7 concludes.

2. Conceptual Framework

In this section, we present a simple conceptual framework based on Bento et al. (2015) that we can use to empirically evaluate the net environmental impact of HFC-23 projects.[6] Our framework differentiates between credited offsets and emissions reductions. We term credits that do not correspond to emissions reductions "over-credited offsets," reductions that do not earn credits "under-credited emissions reductions," and reductions that correspond to credits "perfectly credited emissions reductions."

In Figure 1, a hypothetical project supplies all possible crediting and reduction combinations: over-credited offsets, under-credited emissions reductions, and perfectly credited emissions reductions. The horizontal axis represents the project's crediting period in years, and the vertical axis quantifies emissions in million metric tons of CO_2 equivalent ($MMTCO_2e$). The project has an unobserved business-as-usual path of emissions, depicted by the solid black line. The CDM assigns the project a baseline level of emissions for each crediting period, represented by the dashed black line. In our example, the project emits zero emissions when it produces

[5] We note that five different methodologies have governed the crediting rules for CDM HFC-23 projects. In general, these methodologies become more stringent (less likely to over-credit projects) over time.

[6] Spalding-Fecher et al. (2012) assess the net emissions impact of HFC-23 projects from an ex ante perspective, looking toward the future. The authors do not explicitly account for the perverse incentives that lead to over-crediting of HFC-23 projects. Our analysis differs in that it is from an ex post perspective, looking back at CERs that have already been issued, and comprehensively accounts for incentives that lead to over- and under-crediting of CDM HFC-23 projects.

credits. The solid and dashed lines do not necessarily overlap, for many reasons, including regulator uncertainty over BAU emissions.

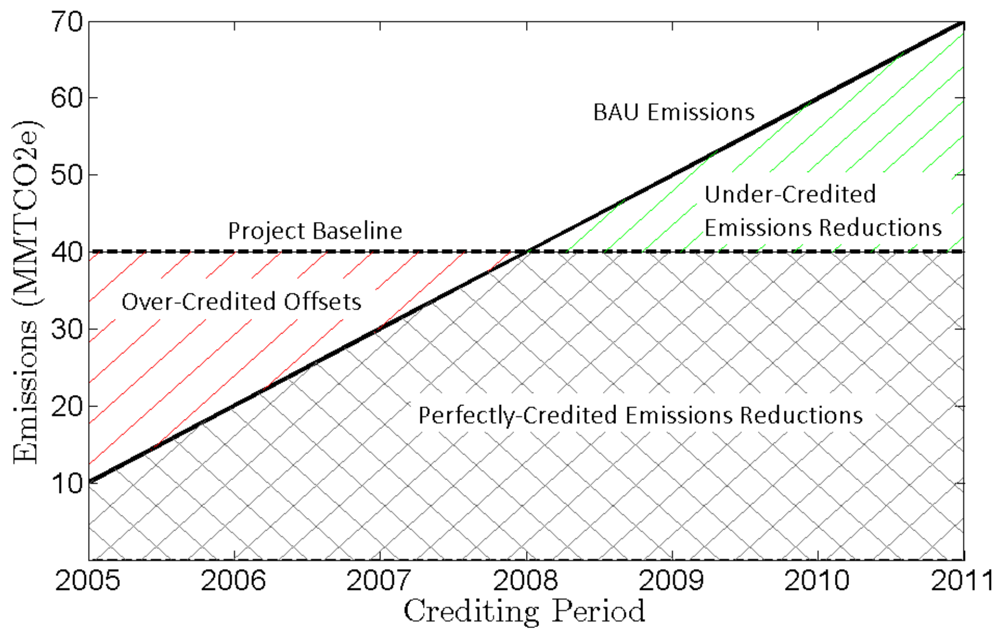
In this example, the CDM regulator has overestimated BAU emissions in crediting periods from 2005 to 2009 and underestimated BAU emissions in crediting periods after 2009. Overestimation leads to awarding the project with over-credited offsets, the total quantity of which equals the red area. Underestimation leads to awarding the project with under-credited emissions reductions, the total quantity of which equals the green area. Perfectly credited reductions (gray area) occur when the CDM issues credits for reductions. The net emissions impact of any offset project equals the difference between the red and green areas, assuming polluters use all offset credits for compliance. If this difference is negative (positive), then the project leads to an overall decrease (increase) in emissions. Past literature describes such projects, which are awarded fewer credits than the emissions they reduce, as providing “net atmospheric benefits” (Schneider 2009). Absent from the literature is an ex post analysis based on observed offset data of the relative magnitudes of under-credited emissions reductions compared with over-credited offsets.

The net emissions impact of the hypothetical project summarized by the characteristics in Figure 1 is equal to the difference between the mass of under-credited emissions reductions and the mass of over-credited offsets. If the mass of under-credited emissions reductions exceeds the mass of over-credited offsets, then the project leads to a net reduction in global emissions. If the reverse is true, then the project leads to a net increase in global emissions.

Next, we use our framework to understand how perverse incentives and project designs can change the composition of under-credited emissions reductions and over-credited offsets. We begin by evaluating how perverse incentives in the context of moral hazard encourage the supply of over-credited offsets. The most salient example of moral hazard is the case when projects are able to inflate their assigned baselines by increasing emissions during the baseline-setting period. This is visualized by a project’s baseline being artificially increased. In Figure 1, this is where the horizontal line Project Baseline shifts up. As a result, the shaded mass of over-credited offsets increases, while the shaded mass of under-credited emissions reductions falls.[7] The overall effect of this movement when these offsets are sold and used for compliance is an increase in GHG emissions.

[7] The mass of perfectly-credited offsets increases as well, but these types of offsets have no net emissions impact.

Figure 1. Crediting of a CDM Offset Project



Notes:
1. Our example CDM offset project has BAU emissions increasing over time (solid black line) and a constant annual baseline (dashed black line).
2. This project reduces its emissions to zero once it opts in to the program, so the annual quantity of offsets awarded equals the project's annual baseline.
3. Over-credited offsets equal the difference between the project's baseline and its BAU emissions (red region). Perfectly credited reductions equal the minimum of the project's BAU emissions and the project's baseline (gray region). Under-credited emissions reductions equal the difference between the project's BAU emissions and its baseline (green region).

We then evaluate how perverse incentives in the form of adverse selection may increase emissions. When project managers have greater information on their own BAU emissions relative to the CDM project design, there is a greater incentive for managers with relatively high BAU emissions to opt in and earn credits. A project with relatively high BAU emissions is represented by a shift down of the positively sloped BAU Emissions line in Figure 1 so that this line lies below the Project Baseline for most of the crediting schedule. Similarly to the case of moral hazard, adverse selection has the effect of increasing the mass of over-credited offsets and decreasing the mass of under-credited emissions reductions, thereby increasing GHG emissions when these offsets are sold and used for compliance.

Finally, we show how project designs can alter the composition of over-credited offsets versus under-credited emissions reductions. In many CDM project designs, project baselines are set conservatively below expected BAU emissions to account for modeling uncertainty. This is equivalent to a project design setting a baseline that is potentially well below what is illustrated in Figure 1. This has the effect of increasing the mass of under-credited emissions reductions and reducing the mass of over-credited offsets, thereby counteracting the effects that stem from perverse incentives. The overall emissions impact of offset programs therefore depends on the relative magnitude of perverse incentives and conservative baseline setting. We incorporate both effects to provide a comprehensive estimate of the net environmental impact of offset programs.

Before proceeding, we must clarify an important distinction between additionality and crediting. Gillenwater (2012b) defines additionality as the property of an activity being additional, which means the recognized policy interventions are deemed to be causing the activity to take place. The installation of capture and thermal oxidation technology must be caused by the CDM issuing offset credits for HFC-23 projects to be deemed additional. We consider only whether economic trends may have caused installation and assume that other trends (such as preexisting policies, strategic games, or financial attractiveness of the technology) did not prompt HCFC-22 plants to install capture and thermal oxidation technology.[8] Instead, we focus on crediting, which refers to how much the activity has improved performance (Gillenwater 2012a)—that is, to what extent the capture and thermal oxidation technology reduced HFC-23 emissions at HCFC-22 plants involved in the CDM.

3. Carbon Offset Crediting in the Context of CDM HFC-23 Projects

Both HCFC-22 and HFC-23 emissions are potent greenhouse gases with estimated global warming potentials (GWPs) equal to 1,810 and 14,800, respectively, over a 100-year time period (Forster et al. 2007). HFC-23 is an unwanted and unavoidable by-product in the production of HCFC-22, which is widely used in air-conditioning, commercial refrigeration, and foam insulation (termed “dispersive production”) and the manufacture of fluoropolymers (termed “feedstock production”) (Fang et al. 2014). While the ratio at which HFC-23 is produced as a by-product of HCFC-22 production (termed “coproduction ratio”) can exceed 4 percent at HCFC-22 plants, operators in the United States have lowered coproduction ratios to 1.5 percent and 3.0 percent by optimizing their processes (Irving and Branscombe 2000), with one particularly

[8] Given that the installation of thermal oxidation technology imposes significant costs, we find it highly likely that participation in the CDM is the sole cause of firms in developing countries adopting this technology. Another possibility is government mandate of this technology, but we find no evidence of such mandates in China and Mexico between 2006 and 2013.

advanced and large HCFC-22 plant achieving a coproduction ratio of 1.37 percent (McCulloch 2005). The scope of process optimization, however, is limited by technical and economic considerations. Moreover, process optimization itself cannot eliminate HFC-23 emissions (McCulloch and Lindley 2007).

Instead, the KP requires that HFC-23 projects that voluntarily participate in the CDM install thermal oxidation technology, which captures and destroys HFC-23 emissions from HCFC-22 plants. Thermal oxidation technology virtually eliminates HFC-23 emissions (Irving and Branscombe 2000) but requires an initial investment of around US$13.6 million and an annual operating and maintenance cost of ~US$35,000 (Zhu 2014). To date, the CDM has issued credits worth 540 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) to 19 HFC-23 projects between February 2006 and July 2015 (Fehnann 2015). Table 1 contains basic information about the 12 projects we consider in our empirical analysis.[9]

Table 1. Clean Development Mechanism Hydrofluorocarbon-23 (HFC-23) Projects

Project #	Location	Projected annual M CERs	Registration date	Start of crediting period	End of crediting period	Methodology
11	China	8.4	Jun 06	Dec 06	Nov 13	AM0001 V3
151	Mexico	2.2	Jun 06	Jun 06	Jun 13	AM0001 V3
193	China	5.8	Mar 06	Aug 06	Jul 13	AM0001 V3
232	China	10.1	Mar 06	Jan 07	Dec 13	AM0001 V3
306	China	10.4	Aug 06	Dec 06	Dec 13	AM0001 V3
549	China	3.7	Oct 06	Nov 06	Oct 13	AM0001 V4
550	China	4.8	Oct 06	Jan 07	Oct 13	AM0001 V4
767	China	2.1	May 07	May 07	Apr 14	AM0001 V4
868	China	4.8	Apr 07	Apr 07	Apr 14	AM0001 V5
1105	China	3.5	Feb 08	May 08	Apr 15	AM0001 V5
1194	China	4.2	Sep 07	Sep 07	Sep 14	AM0001 V5
1947	China	7.9	Apr 09	Apr 09	Apr 16	AM0001 V5

Source: UNFCCC (2015).
Notes: Project 3 in Korea uses a methodology similar to the 12 projects we consider in our analysis, but the CDM had yet to issue it sufficient monitoring reports to determine whether it had received CERs at the time of our analysis. We therefore exclude this project.

[9] We have chosen to exclude eight projects for data or methodological reasons that we explain in Section 4.

The prevalence of these projects results from their profitability, which hinges on scientific and economic determinations. A one ton reduction of HFC-23 emissions earns CDM project developers 11,700 CERs—a number equal to HFC-23's GWP as estimated in the late 1990s—because the Kyoto Protocol allows trading among greenhouse gas pollutants (Wara 2008). Combined with comparatively low marginal costs of abating HFC-23 and relatively high historical CER prices, HFC-23 projects have enjoyed large profits from participating in the CDM (Schneider 2011), leading to criticisms that the CDM overcompensates HFC-23 projects (Zhang and Wang 2014) and calls for switching from an offsetting mechanism to more direct financing of thermal oxidation technology (Wara and Victor 2008).

These two criticisms have mired CDM HFC-23 projects in controversy (Zhang and Wang 2014). In 2005, recognizing the large profit margins that participating HCFC-22 plants would receive, the Chinese government placed a 65 percent tax on the revenue earned from CDM HFC-23 projects (Zhu 2014). Popular media started to pick up on the work of Wara (2008), Schneider (2011), and others in the late 2000s and early 2010s (*Economist* 2010; Rosenthal and Lehren 2012), leading to the belief that the CDM incentivized the construction of new HCFC-22 plants (Böhm and Dhabi 2009), which is wrong, as the CDM prohibits new HCFC-22 plants from participation (Michaelowa 2011). The European Commission then banned companies regulated by the European Union Emissions Trading System (EU ETS) from using CERs from HFC-23 projects after April 2013 (EC 2011). The New Zealand ETS also banned regulated companies from using CERs from HFC-23 projects, starting in December 2012 (New Zealand Government 2012).[10] While these projects collectively reduced ~620 $MMTCO_2e$ during their first crediting periods, they will emit ~112 $MMTCO_2e$ annually if they choose not to participate in a second crediting period under the CDM (Fang et al. 2014). It is therefore timely to review the critiques of HFC-23 projects.

It is possible to reduce HFC-23 emissions from HCFC-22 plants in developing countries at lower costs than with an offsetting mechanism, but a policy has yet to emerge to fully replace the CDM. A proposal to amend the Montreal Protocol (MP) would require developing countries to freeze HFC-23 emissions at baseline levels by 2020 and reduce them 70 percent, 40 percent, and 15 percent by 2025, 2031, and 2045, respectively. As part of that proposal, HCFC-22 plants not participating in the CDM would be eligible for direct financing under the MP's Multilateral

[10] In response to these bans, it is unclear whether HCFC-22 plants will renew their crediting periods—most of which have expired or are about to expire—and continue to reduce HFC-23 emissions (Lin, Cui, and Yang 2013).

Fund (UNEP 2014). Its adoption could lead to more cost-effective HFC-23 reductions from HCFC-22 plants in developing countries, if the level of subsidy is lower than that provided by the CDM. The MP might cause HFC-23 reductions indirectly in the more immediate future, but only to a limited extent. Specifically, the MP started regulating the dispersive—but not feedstock—production of HCFC-22 in developing countries in 2013 by requiring a freeze relative to baseline levels in that year and a 10 percent, 35 percent, 67.5 percent, and 97.5 percent reduction in production by 2015, 2020, 2025, and 2030, respectively (Fang et al. 2014).[11] Fang et al. (2014) predict that HCFC-22 production for dispersive uses in China will decrease because of this regulation, but that overall HFC-23 emissions will increase because of an increase in the production of HCFC-22 for feedstock uses.[12]

CDM Baseline Methodologies for Crediting of HFC-23 Projects

The CDM regulators designed methodologies that assign each HFC-23 project a conservative baseline emissions level that determines its maximum annual earnable amount of offset credits. To date, there have been six versions of this methodology, but we focus on versions 3 through 5 because they contain similar provisions and the HCFC-22 plants they cover are responsible for the majority (~84 percent) of regulated HFC-23 emissions (UNFCCC 2015).

In these methodologies, CDM regulators assigned baseline emissions levels based on behavior of eligible HCFC-22 plants that they observed during a 2001–04 baseline-setting period. Importantly, these methodologies ban from participation plants that did not operate for at least three years of the baseline-setting period, effectively preventing new HCFC-22 plants from earning CERs. Assigned baseline emissions levels for most projects (17 out of 20) equaled the product of the maximum observed value of HCFC-22 production during the baseline-setting period and the lower of either the minimum observed coproduction ratio during the baseline-setting period or a default 3 percent coproduction ratio (UNFCCC 2005).

These methodologies create perverse incentives and incentivize over-credited offsets. Specifically, although the HFC-23 program was first announced in 2003, CDM regulators assigned baseline emissions levels to projects based on emissions through 2004—giving project managers an opportunity to intentionally ramp up HFC-23 emissions beyond BAU levels during

[11] The MP regulates many HCFCs beyond HCFC-22.

[12] See Figure 4 in Fang et al. (2014) for more detail.

the last year or more of the baseline-setting period to receive an artificially high assigned emissions baseline level. Wara (2008) provides evidence that HCFC-22 plants participating in the CDM indeed ramped up their HFC-23 emissions by modifying either HCFC-22 production levels or coproduction ratios during the baseline-setting period, from 2001 to 2004. An HCFC-22 plant manager could view the cost associated with such modifications as small compared with the large profits it might enjoy from additional CERs. These artificially inflated assigned baseline emissions levels lead to crediting of emissions reductions that require no abatement effort, thereby prompting supply of over-credited offsets.

These CDM methodologies also create perverse incentives for particular plants to opt in to the program. Schneider (2011) explores instances where an HFC-23 project dramatically reduced or even stopped HCFC-22 production during a crediting period if that plant could not earn any more CERs. This highlights the unlikely possibility that some plants that opted in to the CDM had BAU HFC-23 emissions equal to zero, which would indicate dramatic adverse selection. More likely, these plants still would have produced HFC-23 emissions in their BAU, albeit at a level lower than under the CDM.

But high profit margins and imperfect methodologies do not ensure that the CDM, *on net*, over-credits HFC-23 projects. In fact, recent literature highlights that high profit margins for carbon offsets can incentivize projects to supply under-credited reductions if assigned baselines are lower than BAU emissions. Although such a project would have to reduce emissions without reward until it lowered emissions below its conservative assigned baseline, profits from the credits earned by the project could far outweigh the costs of abating emissions without credit (Bento et al. 2015).

We argue that this mechanism exists for HFC-23 projects and prompts supply of under-credited offsets for two reasons. First, regulators chose the minimum observed coproduction ratio during the baseline-setting period, or a lower value if the observed coproduction value exceeded a default value, in an effort to provide for a conservative calculation of assigned emissions baselines. Second, assigned emissions baselines remained constant over time despite numerous projections that anticipated substantial HFC-23 growth (McCulloch 2005; Miller and Kuijpers 2011). Both of these factors led to assigned baselines that were lower than BAU emissions. Given this possibility and the presence of high profit margins, evidence suggests that CDM methodologies incentivized the supply of under-credited emissions reductions.

The CDM clearly created incentives for both the supply of over-credited offsets and under-credited emissions reductions. Our main contribution is to quantify the magnitudes of both supplies empirically to estimate the net emissions impact of CDM HFC-23 credits. We also aim to assess the relative impact of moral hazard and adverse selection on the supply of over-credited offsets.

4. Modeling Approach and Data

We collected data from an online database that monitors the progress of all CDM projects, called the CDM Project Cycle Search (UNFCCC 2015). A total of 20 registered HFC-23 projects receive CERs, but we excluded 8 projects.[13] First, we excluded 2 projects that followed versions 1 and 2 of the CDM methodology governing HFC-23 crediting, because these earlier methodologies did not place a limit on the amount of earnable credits based on maximum HCFC-22 production during the baseline-setting period. We therefore could not compute their HFC-23 emissions during the baseline-setting period, which prevented us from constructing BAU HFC-23 emissions projections. These two projects contributed ~5 percent of expected annual HFC-23 emissions from HCFC-22 plants participating in the CDM. Second, we excluded five projects because they did not report data on HCFC-22 production or coproduction ratios, which also prevented us from constructing BAU HFC-23 projections. These five projects contributed ~11 percent of expected annual HFC-23 emissions from HCFC-22 plants participating in the CDM. Third, we excluded a single small project because the CDM had not issued that sufficient monitoring reports at the time of our analysis and we therefore could not verify whether it had CERs. The projects we consider therefore contributed ~84 percent of expected annual HFC-23 emissions regulated by the CDM.

As displayed in Table 1, 11 of the 12 HFC-23 projects we consider are located in China, as are 95 percent of expected HFC-23 emissions resulting from CDM projects. CDM methodologies effectively ban HCFC-22 plants constructed in 2003 or thereafter from participation. All eligible plants ended up participating in the CDM as HFC-23 projects, despite the 65 percent tax on CER revenues imposed by the Chinese government (Zhu 2014). Each project owner must register with the CDM before receiving a crediting period, which is renewable and lasts for 7 or 10 years. For each period, project developers apply a baseline methodology approved by the CDM executive board, which is valid for the duration of the crediting period, and a project-specific annual baseline emissions level based on behavior

[13] We count Project 3 as two projects since it used a methodology that we do not consider in this analysis for one of its crediting periods and a methodology that we do consider in this analysis for another of its crediting periods.

observed during a 2002–2004 baseline-setting period. Each plant's baseline remains constant for the entire period. At the end of each year, a project receives CERs equal to the difference between its assigned baseline level and observed level of emissions. If an HFC-23 project reaches either the maximum HCFC-22 production or coproduction ratio observed during the baseline-setting period, it cannot earn any additional CERs for that period (UNFCCC 2005).

To empirically quantify the crediting of HFC-23 offsets, we must determine three project-specific components: observed emissions, assigned baseline emissions levels, and BAU emissions. To attempt to discern their relative impacts, we must also create a methodology that allows for identifying the extent to which moral hazard and adverse selection contributed to the supply of over-credited offsets.

Observed Emissions

We assume that observed emissions for HFC-23 projects equals zero when they supply credits, for two reasons. First, the capture and thermal oxidation of HFC-23 are highly effective and virtually eliminate HFC-23 emissions.[14] Second, CDM monitoring reports collected from the UNFCCC's online database confirm negligible estimated amounts of emissions leakage resulting from HFC-23 mitigation (UNFCCC 2015).

Assigned Baselines

CDM regulators assigned project-specific baseline emissions levels based on the maximum observed value of HCFC-22 production during the 2002–2004 baseline-setting period and the lower of either the minimum observed coproduction ratio during the 2002–2004 baseline-setting period or a default 3 percent HCFC-22 coproduction ratio.[15] The HFC-23 value that results from multiplying these two parameters closely represents the maximum annual amount of CERs for a specific HCFC-22 plant. We use this value when we want to replicate the

[14] For example, tests showed that thermal oxidation destroyed over 99.996% of HFC-23 emissions (Irving and Branscombe 2000; McCulloch and Lindley 2007).

[15] Three versions of the CDM HFC-23 methodologies differ substantially from the versions we consider in this paper. Version 6 assigns baselines in the same manner as versions 3 through 5 but applies an especially conservative default coproduction ratio of 1% (Erickson et al. 2014). Versions 1 and 2 did not assign baselines based on a baseline-setting period during 2001–04. Instead, these methodologies limited the quantity of earnable credits in a given year to the plant-level production of HCFC-22 for that year multiplied by the lowest value for the coproduction ratio or a maximum value of 4%.

process regulators used to assign baselines—a process that fully incentivizes moral hazard and adverse selection. But we modify this approach when we estimate the relative impact of moral hazard and adverse selection.

Business-as-Usual (BAU) Emissions Scenarios

We calculate plant-specific BAU HFC-23 emissions projections that represent emissions levels in the absence of the CDM. We derive two of our project-specific projections, denoted as the Low and High scenarios, from aggregate projections for developing countries presented in McCulloch (2005), which, to the best of our knowledge, provides the only BAU HFC-23 emissions projections specifically tailored to developing countries. McCulloch et al. (2006) and McCulloch and Lindley (2007) further elaborate and strongly rely on the methodology employed by McCulloch (2005).

Ideally, we would use projected HFC-23 emissions for each CDM project instead of using an aggregate projection for all HFC-23 emissions in developing countries. Unfortunately, the existing literature does not provide plant-specific projections for future HFC-23 emissions, and thus we consider the Low and High scenarios to provide the most appropriate estimation of future HFC-23 emissions for the CDM plants considered in our analysis, for two reasons. First, the CDM projects we consider contribute to the HFC-23 emissions projected in our Low and High scenarios; in 2002, for example, the 12 plants we analyze produced 4,631 tons of HFC-23 (CDM Project Cycle 2015), which amounts to 72 percent of estimated HFC-23 emissions from developing countries (McCulloch 2005). Second, we view the assumptions made by McCulloch (2005) as reasonable, and we introduce and defend them in the next subsection.

We assign a third project-level BAU HFC-23 emissions projection, an Intermediate scenario, to serve as a middle-of-the-road scenario in between our Low and High scenarios. This scenario involves modest annual growth in emissions until 2008 and zero emissions growth thereafter. It was suggested to us by Archie McCulloch (2013), an expert on HFC-23 emissions growth, as a reasonable growth rate at an individual HCFC-22 plant. It complements our other scenarios—which rely on projections of aggregate BAU HFC-23 emissions—by providing a projection for an individual plant.

For each scenario, we first derive the projected annual growth rate for HFC-23 emissions in 2003, then multiply HFC-23 emissions observed at each CDM plant in 2002 by 1 plus the annual growth rate, giving us the 2003 BAU HFC-23 emissions for each plant. We estimate

BAU emissions in this way for each plant from 2003 to 2013 for all three scenarios. Table 2 shows the annual growth rates we apply to CDM projects for each scenario.

Table 2. Aggregate Business-as-Usual HFC-23 Emissions in Developing Countries (in ktons)

Year	Low	Annual growth	Intermediate	Annual growth	High	Annual growth
2002	6.4	Observed	6.4	Observed	6.4	Observed
2003	7.4	16%	6.7	4.6%	7.4	16%
2004	8.4	14%	7.0	4.6%	8.4	14%
2005	8.6	2%	7.3	4.6%	9.5	13%
2006	8.6	0%	7.6	4.6%	10.5	11%
2007	8.4	–2%	8.0	4.6%	11.6	11%
2008	8.1	–4%	8.0	0%	12.6	9%
2009	7.5	–7%	8.0	0%	13.6	8%
2010	6.7	–11%	8.0	0%	14.7	8%
2011	5.8	–13%	8.0	0%	15.7	7%
2012	4.7	–19%	8.0	0%	16.7	6%
2013	3.4	–28%	8.0	0%	17.8	7%
Total	84.0		91.0		145.0	

Assumptions for BAU Emissions Scenarios

To project BAU HFC-23 emissions in developing countries, McCulloch (2005) makes five assumptions. The two projections that he develops inform our Low and High scenarios and differ only in the last of the five assumptions: the speed at which thermal oxidation technology deploys over time.

The first assumption is that developed countries would dramatically reduce their use of HCFC-22 through 2015 to comply with the MP, while production of HCFC-22 in developing countries would remain unaffected by the MP through 2015. In 2007, however, parties to the MP agreed to freeze HCFC-22 production associated with dispersive uses in developing countries starting in 2013 at baseline levels averaged between 2009 and 2010—with a scheduled reduction of 10 percent in 2015, 35 percent in 2020, 67.5 percent in 2025, and 97.5 percent by 2030 (Fang et al. 2014). HCFC-22 production and therefore HFC-23 emissions associated with feedstock purposes would be unconstrained, however. Nonetheless, the freeze in developing country production of HCFC-22 in 2013 does conflict with the assumption made in McCulloch (2005).

However, we recorded CDM crediting only up to 2013 in our analysis and thus avoided counting reductions that the MP may have caused. We therefore view the assumption that HCFC-22 production in developing countries remains unaffected by the MP as reasonable over the time frames in our analysis.

The second assumption that McCulloch (2005) makes is that developing countries will continue to produce HCFC-22 at a linear growth rate of approximately 26,000 tons per year from 2002 through 2015, with the vast majority of that growth originating from China. McCulloch and Lindley (2007) adopted a similar linear growth rate for developing countries. Lin et al. (2013) report data on HCFC-22 production in China that shows an average rate of growth equaling nearly 50,000 tons per year from 2002 through 2010. Similarly, Fang et al. (2014) report an average annual growth of HCFC-22 production in China that equals nearly 40,000 tons between 2000 and 2012. We therefore view this assumption as reasonable and quite conservative.

The third assumption is that existing plants in developing countries would operate at a coproduction ratio of 2 percent, an approach similar to that taken by McCulloch and Lindley (2007). The weighted average coproduction ratio of the 12 CDM projects we analyze equaled 3.2 percent in 2002, when plant owners did not yet know about the CDM, and equaled 2.83 percent in 2012, revealing a slight improvement over time (Fang et al. 2014). In the United States, Irving and Branscombe (2000) find that plants that are fully optimized to reduce HFC-23 emissions exhibit a range of coproduction ratios between 1.5 percent and 3 percent. McCulloch (2005) finds a low coproduction value of 1.37 percent for a large HCFC-22 plant in a developed country, arguing that it is likely to represent the minimum level of HFC-23 abatement achievable through process optimization. In addition, Oram et al. (1998) find that from 1960 to 1995, HFC-23 emissions occurred at 2.1 percent the volume of HCFC-22 produced; this was during a time when substantial amounts of HFC-23 were captured to produce halon-1301, the production of which the MP effectively banned since. We therefore find that an assumed 2 percent coproduction ratio for existing plants is not only reasonable but also slightly optimistic.

The fourth assumption is that new plants in developing countries would operate at a coproduction ratio of 4 percent. Irving and Branscombe (2000) find that plants in the United States that are not fully optimized to reduce HFC-23 emissions exhibited a coproduction ratio range from 3 percent to 4 percent. Although there is generally more effort in developed countries to reduce HFC-23 emissions through domestic initiatives and regulations, an assumed coproduction ratio of 4 percent essentially assumes an absence of rudimentary abatement procedures (McCulloch and Lindley 2007). We therefore view this assumption as reasonable but also slightly pessimistic.

The fifth assumption concerns the speed at which thermal oxidation technology deploys over time. The Low BAU HFC-23 projection differs from the High projection only in that it assumes complete adoption of thermal oxidation technology starting in 2005 and ending in 2015. The High BAU HFC-23 projection assumes no deployment of thermal oxidation technology (McCulloch 2005). We view this assumption as appropriate because, to the best of our knowledge, no facilities in developing countries have deployed thermal oxidation technology outside of the CDM, and no stringent policies are in place to encourage the installation of such technology.

The annual growth rate for our Intermediate BAU emissions scenario is derived from the possibility that an individual HCFC-22 plant might increase HFC-23 emissions up to 25 percent over five years. A project manager might achieve this increase through improvements in maintenance that result in longer periods of operation, changes in operating conditions, and removal of HCFC-22 production bottlenecks (McCulloch 2013).

Modeling Perverse Incentives

Assigned emissions baselines represent the constant, maximum amount of emissions for which regulators allow HFC-23 projects to receive CERs. We construct three cases for assigned emissions baselines: benchmark, perverse incentives, and strong perverse incentives.

Our benchmark case represents a CDM without moral hazard or adverse selection and thereby constitutes an ideal situation that yields the highest amount of under-credited emissions reduction. When comparing our benchmark case with our BAU emissions scenarios, we calculate assigned baselines by projecting plant-level HCFC-22 production observed in 2002 by annual HCFC-22 growth estimates provided by McCulloch (2005) and assuming that observed coproduction ratios remain constant during the baseline-setting period. In all cases, we avoid the influence of moral hazard and adverse selection on the HFC-23 project's behavior during the baseline-setting period by assigning baselines according to behavior expected without the CDM's influence. The benchmark case therefore effectively constructs a counterfactual to baselines actually assigned by the CDM. We finally apply CDM rules to this counterfactual baseline-setting period data to determine assigned baselines.

Our perverse incentives case most likely represents the CDM as implemented. To assign baseline emissions under a perverse incentives case, we use observed HCFC-22 production and coproduction ratios during the baseline-setting period. By using data observed during the baseline-setting period rather than counterfactual data that represents the HFC-23 project's behavior without the CDM, our data captures any influence moral hazard had on HCFC-22 production and coproduction ratios, as indicated by Wara (2008). We then apply CDM rules to determine assigned baselines, similar to those actually assigned by the CDM.

Our strong perverse incentives case might represent the CDM as implemented if moral hazard and dramatic adverse selection were present. To account for adverse selection, we revisit Schneider (2011), who cites instances where one project, known as plant 767, dramatically reduced or even stopped HCFC-22 production during a crediting period when no more CERs could be earned. This observation opens up the possibility, even if an unlikely one, that plant 767 remained open just to produce HCFC-22 for CDM HFC-23 credits and therefore supplied only over-credited offsets. We create specific criteria exemplifying plant 767's behavior: a plant that decreases its monthly HCFC-22 production to less than 25 percent of its average after reaching its maximum potential HCFC-22 production available for HFC-23 crediting under the CDM. Given these criteria, we also identify plant 151 as exhibiting similar behavior. We classify both plants as being adversely selected by CDM regulators because of an information asymmetry that left regulators overestimating their BAU emissions. We then set these two projects' BAU HFC-23 emissions equal to zero and replicate the process that we used to assign baselines for the perverse incentives case. The strong perverse incentives case results in the highest number of over-credited offsets.

Empirical Quantification of Crediting

Fang et al. (2014) investigate monitoring reports for CDM HFC-23 projects and find that estimated abatement is on average 20 percent greater than the number of CERs issued to participating plants. However, we cannot rule out that CDM methodologies may have influenced observed HFC-23 emissions. We therefore prefer our approach of comparing BAU HFC-23 emissions scenarios with assigned baselines under different scenarios.

For each year a CDM project receives credits between 2006 and 2013, we compare the assigned baseline emissions levels under the three cases with our three scenarios for BAU emissions levels to determine the magnitudes of perfectly credited reductions, over-credited offsets, and under-credited emissions reductions (the start of a project's crediting period varies from 2006 to 2009). This allows us to calculate the relative supply of these crediting combinations, as well as the impact of perverse incentives, by comparing these nine estimates.

We must make two caveats. First, the data availability for CDM HFC-23 projects is not ideal. For example, project-specific data exists only for plants that participated in the CDM and does not include historical emissions or HFC-23 abatement costs. This hampers our ability to pursue a statistical methodology, such as that employed by Montero (1999). Second, our findings are specific to HFC-23 plants and may be generalizable, if at all, only to offset projects that exhibit characteristics similar to those of HFC-23 projects, including exceptionally low marginal abatement costs and an exceedingly high mitigation potential.

5. Results

Our key results appear in Table 3, with additional project-specific results presented in Tables A2, A3 and A4 in the Appendix. We consider three cases that represent different levels of perverse incentives under the CDM: our benchmark case, which does not include moral hazard or adverse selection and therefore represents an idealized CDM; our perverse incentives case, which most likely represents the CDM as implemented; and our strong perverse incentives case, which might represent a CDM under dramatic adverse selection. For each case, we consider three BAU emissions scenarios: a Low scenario, which assumes that HCFC-22 plants quickly adopt thermal oxidation technology and thereby rapidly reduce HFC-23 emissions, even in the absence of the CDM; a High scenario, which assumes that HCFC-22 plants increase HFC-23 emissions over time but at a declining rate; and an Intermediate scenario based on an expert's opinion regarding HFC-23 growth at a single HCFC-22 plant, which serves as a check against our Low and High scenarios.

We estimate under a variety of scenarios and cases that CDM HFC-23 projects have resulted in emissions impacts ranging from a 147 $MMTCO_2e$ net emissions increase to a 555 $MMTCO_2e$ net emissions decrease. In addition, we find it likely that the supply of under-credited emissions reductions closely equals the supply of over-credited offsets, meaning that CDM HFC-23 credits maintain their environmental integrity on average. The failure to consider the supply of under-credited emissions in the context of CDM HFC-23 projects therefore exaggerates the influence of perverse incentives created by CDM methodologies that lead to over-credited offsets. Moreover, the supply of under-credited emissions is substantial as a result of safeguards in CDM methodologies that incentivized the assignment of conservative emissions baselines for HFC-23 projects and high profit margins by HFC-23 project per credit. While the strength of incentives to supply over-credited offsets overpowered these more beneficial incentives in certain cases, they should not be ignored.

Table 3. Crediting for Clean Development Mechanisms HFC-23 Projects, 2006–2013 (in tons HFC-23)

Case	Category of supply	BAU emissions scenario		
		Low	Intermediate	High
1. Benchmark	Perfectly credited offsets	30,620	36,412	38,032
	Under-credited emissions reductions	2,928	5,129	37,495
	Over-credited offsets	7,411	0	0
	Total offset supply	38,031	36,412	38,032
	Net emissions impact	4,483	–5,129	–37,495
		Low	Intermediate	High
2. Perverse Incentives	Perfectly credited offsets	30,043	35,601	41,339
	Under-credited emissions reductions	3,507	5,941	34,187
	Over-credited offsets	11,484	5,926	187
	Total offset supply	41,527	41,527	41,527
	Net emissions impact	7,977	–15	–34,000
		Low	Intermediate	High
3. Strong Perverse Incentives	Perfectly credited offsets	27,930	33,135	38,650
	Under-credited emissions reductions	3,650	5,656	31,899
	Over-credited offsets	13,596	8,392	2,877
	Total offset supply	41,527	41,527	41,527
	Net emissions impact	9,946	2,736	–29,022

Notes:
1. The Low and High BAU emissions scenario cases are taken from McCulloch (2005). The Intermediate scenario is based on correspondence with Archie McCulloch (2013), an expert on HFC-23 emissions.
2. Perfectly credited offsets occur when a credit is awarded for an emissions reduction; under-credited emissions reductions occur when a credit is not awarded for an emissions reduction; and over-credited offsets occur when a credit is awarded for no emissions reduction.
3. Total offset supply is equal to the sum of supply of perfectly credited offsets and over-credited offsets.
4. Net emissions impact represents the emissions deficit or surplus resulting from HFC-23 projects. It is equal to zero when all offsets are perfectly credited, positive when offsets are net over-credited, and negative when reductions are net under-credited. A negative net emissions impact implies that HFC-23 projects, on average, received less credit than emissions reduced.

Our benchmark case represents an idealized CDM without perverse incentives stemming from moral hazard or adverse selection, and therefore this case yields the maximum amount of under-credited reductions. In the benchmark case, we find positive supplies of over-credited offsets only in the Low emissions scenario, and all three scenarios supply under-credited emissions reductions. In the benchmark case, our High scenario results in a net emissions reduction of 555 $MMTCO_2e$, which is similar to the annual GHG emissions from the United Kingdom. This value represents our estimate of an idealized outcome if CDM methodologies did not create any perverse incentives, and thus it represents an upper-bound estimate of net emissions reductions.

We argue that our perverse incentives case most likely represents the CDM as implemented. In this case, we find positive supplies of under-credited emissions reductions and over-credited offsets in each of our three BAU emissions scenarios. The ratio of under-crediting to over-crediting for this case ranges from 0.31 in our Low scenario to 183 in our High scenario, with the latter value corresponding to net emissions reductions from CDM HFC-23 projects equaling 503 $MMTCO_2e$, which is slightly smaller than the annual GHG emissions from the United Kingdom. Our Intermediate scenario results in a one-to-one ratio of under-crediting to over-crediting. We therefore find it likely that the supply of under-credited emissions reductions from CDM HFC-23 projects closely equals the supply of over-credited offsets, which implies a zero net emissions reduction.

Our strong perverse incentives case might represent the CDM as implemented if dramatic adverse selection were present. In this case, we find positive supplies of under-credited emissions reductions and over-credited offsets in each BAU emissions scenario. The ratio of under-crediting to over-crediting ranges from 0.27 in our Low scenario to 11 in our High scenario, with the former value corresponding to net emissions increases from CDM HFC-23 projects equaling 147 $MMTCO_2e$.

The results can also illuminate the relative impacts of moral hazard and adverse selection on the magnitudes of over-credited offsets supplied by CDM HFC-23 projects. Across all BAU emissions scenarios, the introduction of moral hazard and adverse selection leads to additional over-credited offsets. Across our three scenarios, the introduction of moral hazard and adverse selection increases over-credited offsets by 3,400 and 2,422 tons of HFC-23, respectively. We therefore find that moral hazard may play a slightly stronger role in supplying over-credited offsets for CDM HFC-23 projects.

6. Discussion

Our results do not necessarily extend to other carbon offset projects. Since HFC-23 projects have particularly low mitigation costs, the choice of HCFC-22 plants to opt in and supply under-credited emissions reductions when baselines are more stringent than BAU emissions might be unique. Other offset projects might not be able to provide significant amounts of under-credited emissions reductions without facing prohibitive profit losses, forcing them not to participate in the CDM. Further research is required to estimate the relative magnitudes of under-credited emissions reductions and over-credited offsets of other offset project types.

Nonetheless, carbon offsets that reduce HFC-23 emissions may increase in importance despite bans from the European Union and New Zealand because HFC-23 emissions are expected to significantly increase in China (which contributed ~77 percent to global HFC-23 emissions in 2010) over the coming decades (Fang et al. 2014). The resulting surplus of HFC-23 CERs has played a role in pushing the Chinese government toward establishing a national cap-and-trade program (Kong and Freeman 2013). The government has created carbon offsets known as Chinese Certified Emissions Reductions (CCERs), and some of the current seven pilot cap-and-trade programs allow regulated companies to use CCERs for compliance (Zhang et al. 2014). Moreover, the government approved use of HFC-23 offsets in 2013 (Reklev 2015). The CERs from HFC-23 projects that have already opted into the CDM may therefore be recycled into CCERs for use within China—a move that could potentially augment demand. It is also possible that financiers could invest in HFC-23 projects at unregulated HCFC-22 plants in China, a proposal similar to that imagined by Michaelowa (2006).

7. Conclusion

We find it likely that, under conservative assumptions regarding BAU HFC-23 emissions at HCFC-22 plants participating in the CDM, the net emissions impact of HFC-23 projects is small, because the CDM awarded a number of CERs nearly equal to emissions reductions by CDM HFC-23 projects—even after accounting for perverse incentives including moral hazard and adverse selection. We attribute these results to the CDM methodology that outlined the design of HFC-23 projects and to the CDM rules that governed HFC-23 crediting. We first find that the CDM methodology sets conservative baselines that are generally lower than projected BAU emissions of HFC-23 projects. In addition, we find that because HCFC-22 plants have exceptionally low marginal cost of abating HFC-23 emissions, they participate in the CDM despite conservative baselines, thereby supplying under-credited emissions reductions.

We provide evidence that suggests it is likely that the supply of under-credited emissions reductions equals the supply of over-credited offsets from CDM HFC-23 projects, implying that these projects maintain their environmental integrity on average. By extending a pre-existing analytical framework established by Bento et al. (2015) through incorporating moral hazard, we comprehensively account for the supplies of over-credited offsets and under-credited emissions reductions provided by CDM HFC-23 projects. We therefore primarily contribute to the existing policy literature on CDM HFC-23 projects (Wara 2008; Schneider 2011), that focuses mainly on over-credited offsets, by accounting for under-credited reductions in accordance with recent advances in the economics literature (Bento et al. 2015; Bushnell 2012; van Benthem and Kerr 2013). Secondarily, we contribute to the economics literature by attempting to quantify the impact of moral hazard and adverse selection on the crediting of a prevalent carbon offset methodology.

One important takeaway is that under-credited emissions reductions cannot be ignored by policymakers. Policies that ban HFC-23 credits purely on the assertion that these projects supply far less reductions than they are credited for are likely unfounded. In addition, disallowing HFC-23 offsets will increase the cost of compliance under an ETS.[16]

One potential way forward would be to directly finance thermal oxidation technology at HCFC-22 plants. This approach has clear advantages over carbon offsetting. It is comparatively more cost-effective if financing covers only the abatement costs, because carbon offsetting awards each ton of avoided HFC-23 emissions (Zhang and Wang 2014). If applied to all projects in a given jurisdiction, it could also avoid creating perverse incentives such as moral hazard and adverse selection. This policy suffers from one drawback, however: someone has to pay for the financing. Under carbon offsetting, the financiers receive CERs in return and can sell or use these for compliance with cap-and-trade programs, which attracts investment.[17] China has shown

[16] Moreover, the two international treaties that impact HFC-23 emissions offer slow and incomplete coverage at best. For example, the KP's CDM methodologies do not allow HCFC-22 plants built after 2003 to receive HFC-23 credits, despite substantial growth from recently constructed plants. Even the HFC-23 emissions currently covered by the CDM will likely fall as HFC-23 projects face an incentive not to renew their expired, or soon-to-expire, crediting periods and to instead release HFC-23 emissions into the atmosphere (Lin et al. 2013). The resulting emissions could equal up to 112 $MMTCO_2e$ worth of annual HFC-23 emissions if HCFC-22 plants choose to emit (Fang et al. 2014). Similarly, although the MP currently regulates HCFC-22 production—and may regulate HFC-23 emissions—in developing countries, coverage is far from complete. For example, the MP regulates dispersive production in developing countries, although production from feedstock will likely grow substantially, along with the associated HFC-23 emissions. In addition, the proposals that would amend the MP to regulate HFC-23 emissions—if agreed to in the first place—would bind for developing countries in 2025.

[17] Several options for funding direct finance of thermal oxidation installations exist. First, the MP could make such funds available through its Multilateral Fund, as embodied in a proposal currently under consideration (UNEP 2014). Second, the Chinese government could use the revenues collected from its CDM HFC-23 to directly pay HCFC-22 plants to install thermal oxidation technology (Lin et al. 2013). Third, bilateral investment might occur between willing nations. Fourth, investments might be achieved through emerging efforts to revitalize climate finance, such as through the Green Climate Fund. Yet none of these options seem imminent.

willingness to potentially subsidize HFC-23 projects already registered under the CDM but has not extended this consideration to plants not registered under the CDM (*Carbon Pulse* 2015).

In the transition toward direct financing, carbon offsetting could still play an important role. Another potential way forward would be to mitigate HFC-23 emissions by incentivizing unregulated HCFC-22 plants to participate in new carbon offset methodologies and tweaking those new methodologies to provide the maximum amount of under-credited reductions. Such methodologies could be established through voluntary or compliance markets and may be able to incentivize thermal oxidation technology adoption at HCFC-22 plants in developing countries that are not renewing their CDM crediting periods, were constructed after 2003, or are unaffected by the MP's current regulations on HCFC-22 or potential regulations on HFC-23. In fact, a voluntary carbon offset methodology that required the destruction of HFC-23 emissions at HCFC-22 plants was published by the Verified Carbon Standard (VCS 2013) before quickly being terminated (VCS 2014).

When designing new HFC-23 offset projects, policymakers should be mindful of important lessons from the CDM. One clear lesson is that offset methodologies should be designed to avoid perverse incentives. HCFC-22 plants were able to artificially inflate their baselines because they found out *during* the baseline-setting period that the CDM would assign baseline emissions levels based on behavior *within* this period. The simplest solution would be to avoid announcing offset projects while baseline-setting period behavior can be manipulated. A more fundamental solution might be to move away from assigning emissions baseline levels specific to individual projects, although assigning standardized baselines may come with important trade-offs—including environmental integrity and time associated with data collection—and design features to be wary of (Spalding-Fecher and Michaelowa 2013; Hayashi and Michaelowa 2013).

In addition, at least two design options can promote the supply of under-credited reductions and improve the net emissions impact of any potential future HFC-23 projects: assigning baselines below business-as-usual emissions; and awarding a discounted number of credits for the reductions a project achieves (Castro and Michaelowa 2010; Schneider 2011). A recent simulation of a carbon offset market under a Waxman-Markey style cap-and-trade system suggests both approaches are effective (Bento et al. 2015). Other strategies to promote under-crediting are available, include using conservative parameters and shortening crediting periods (Erickson et al. 2014; Schneider 2009; Michaelowa 2014).

To be more certain that HFC-23 projects, on average, supply nearly the same amount of credits as reductions they achieve, statistical tests are needed. While some studies have investigated aspects of the CDM empirically (Zhang and Wang 2011; Sutter and Parreno 2007), not enough data are currently available to apply these types of tests to HFC-23 offsets. More publicly available data from HFC-23 projects would allow us to more rigorously determine their net emissions impact.

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Appendix

This appendix provides an extended review of the policy literature on over-credited offsets issued to CDM HFC-23 projects (Section A1), additional illustrations regarding firms' opt-in choices with different assigned baselines (Section A2), and figures that present our results on crediting supplies and the net emissions impact of individual CDM HFC-23 projects (Section A3). Section A4 provides references.

A1. Review of Policy Literature on Over-Credited Offsets Issued to CDM HFC-23 Projects

This section focuses on two papers that provide evidence that the CDM issued over-credited offsets to HFC-23 projects. Wara (2008) compares projections of HCFC-22 production levels (provided by McCulloch 2005) for developing countries to observed HCFC-22 production at CDM HFC-23 plants during the 2002–04 baseline-setting period. Schneider (2011) investigates CDM data and observes that plant-level HCFC-22 production is either less than or nearly equal to a plant's maximum eligibility for CERs. Moreover, Schneider discovers instances where plants dramatically reduced or even stopped HCFC-22 production during a crediting period when no more CERs could be earned. Both Wara and Schneider provide compelling arguments that CDM HFC-23 projects were subject to perverse incentives.

Regarding coproduction ratios, Wara and Schneider both hypothesize that CDM participants maintained ratios near three percent during the baseline-setting period to inflate their baselines. This type of behavior can be viewed as a result of perverse incentives. None of the 12 projects we consider dramatically increased their coproduction ratios during the baseline-setting period and many projects decreased their coproduction ratios. Table A1 displays coproduction ratios for all 12 plants we consider, from 2002 to 2004. Only three plants increased their coproduction ratios between 2004 and 2003: project 11's ratio increased by .09 percent, project 549's by .49 percent, and project 1105's by .20 percent. The remaining nine plants decreased their ratios by .30 percent on average. This evidence suggests that the three percent cutoff may have acted as a floor that prevented further cuts in coproduction ratios, but it does not seem to have acted, on average, as a ceiling under which projects increased their coproduction ratios—at least for the 12 projects we consider.

Table A1. Percentage Changes in Coproduction Ratios, 2002–04

Project #	2002	2003	2004	Change between 2004 and 2002	Change between 2004 and 2003
11	3.03	2.86	2.95	–0.08	0.09
151	2.46	2.53	2.44	–0.02	–0.09
193	5.80	5.44	4.06	–1.74	–1.38
232	2.59	2.47	2.37	–0.22	–0.10
306	3.62	3.54	2.88	–0.74	–0.66
549	3.83	3.39	3.88	0.05	0.49
550	3.03	3.06	3.05	0.02	–0.01
767	3.20	3.16	3.10	–0.10	–0.06
868	3.11	3.05	3.01	–0.10	–0.03
1105	1.87	1.64	1.84	–0.03	0.20
1194	3.14	3.33	2.96	–0.19	–0.37
1947	3.32	3.24	2.89	–0.43	–0.35

Notes:
1. Data are taken from the monitoring reports of each project, which can be found using the CDM Project Cycle Search (UNFCCC 2015).
2. The HFC-23 program was announced in 2003.

The trend displayed in Table A1 might seem to imply that the CDM encouraged these 12 participating HFC-23 plants to decrease, rather than increase, their coproduction ratios. This seems unlikely and testing such a hypothesis would require additional data. In particular, an estimate that projects ratios during the baseline-setting period would be useful and could be compared with observed data to determine whether coproduction ratio growth was higher or lower than expected. With sufficient data, a statistical test could be constructed to test if observed ratios are explainable within reason. However, in absence of these data, or at least circumstantial evidence, such a claim is untenable.

Regarding HFC-23 emissions, McCulloch (2005) estimates a 13.5 percent growth of HFC-23 emissions in developing countries between 2003 and 2004,[18] approximately the time period when HFC-23 project owners knew about the HFC-23 program and could react to perverse incentives created by the CDM. Calculating HFC-23 emissions for the 12 projects we

[18] The CDM projects we consider represent a significant source, if not a majority, of HFC-23 emissions from developing countries. Including HFC-23 emissions of the other 7 CDM plants, for which methodologies were different and/or data were not available, would likely bring this figure close to 100%, consistent with Wara (2008).

consider by multiplying observed coproduction ratios from the CDM, we find that observed HFC-23 emissions grew 5.5 percent, less than projected in aggregate (UNFCCC 2015).[19] This finding highlights the importance of looking at HFC-23 emissions, the product of HCFC-22 production and coproduction ratios, rather than either variable in isolation. It is entirely possible that an HFC-23 project could increase its HCFC-22 production while decreasing its HFC-23 emissions through lowering its coproduction ratio. One possibility, of course, is that the subset of projects we consider exhibited an HFC-23 emissions growth rate below the estimated aggregate rate. In the main paper, we address more narrow claims regarding inflation of HCFC-22 production at plants participating in the HFC-23 program (which would lead to inflation of assigned baselines and therefore a potential increase in HFC-23 emissions during later crediting periods) and adverse selection of HFC-23 projects.

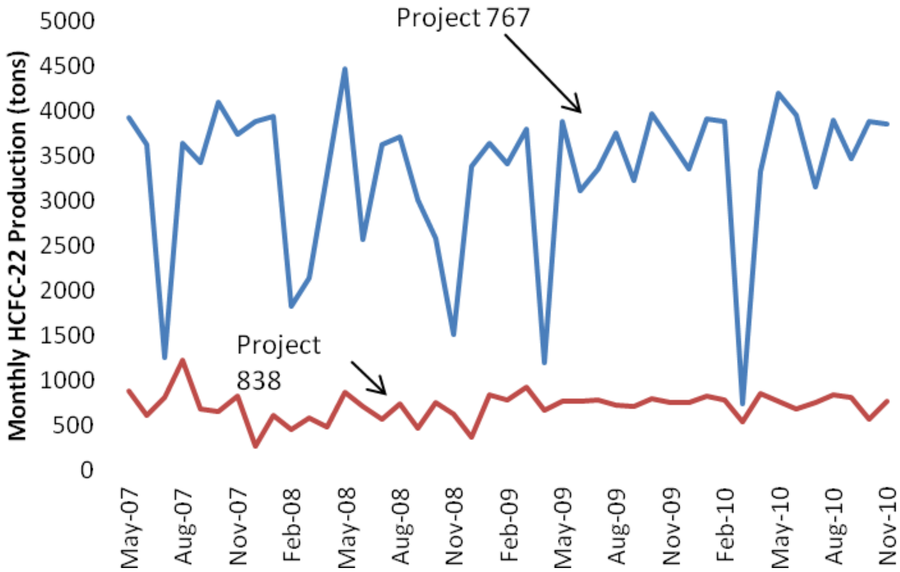
Regarding HCFC-22 production, Wara (2008) finds a 25 percent observed annual average HCFC-22 production rate for 7 HFC-23 projects during the 2002–04 baseline-setting period compared with a 16.5 percent ex ante annual projection for HCFC-22 production in developing countries. This finding implies that HFC-23 projects may have been purposely ramping up their HCFC-22 production during the baseline setting period to inflate their assigned baselines.

The most compelling figure in Schneider (2011) is re-created in Figure A1. We have added project 838 to the original figure, which showed only project 767, for comparison and because both projects started in May 2007, have data up until November 2010, and were assigned April as the last month when CERs could be claimed for that year. Schneider explains that project 767 drastically reduced HCFC-22 production, even stopping production completely some days, near April, after its maximum amount of HFC-23 CERs had been claimed. This would imply that plant 767 was producing HCFC-22 just to receive CERs and purposely inflated its baseline and/or was adversely selected by CDM regulators, which led to over-credited offsets. However, Figure A1 yields two observations. First, the variance of HCFC-22 production does not drastically change *within* a project; it is therefore possible that spikes or dips in production are associated with randomness or events other than CDM rules, perhaps including operation

[19] We also consider projected and observed growth in HFC-23 emissions between 2004 and 2002, in case HFC-23 project owners knew of the HFC-23 program before the announcement. In this case, McCulloch (2005) estimates a 31.3% increase in HFC-23 emissions, while we observed a 29.4% increase in HFC-23 emissions at the 12 plants under consideration.

shutdowns for maintenance. Second, project 838 does not exhibit behavior similar to that of project 767. Specifically, project 838 does not exhibit dramatic dips in production when the end of a crediting period (i.e., April) is near.

Figure A1. Monthly HCFC-22 Production



Notes:
1. Data are taken from the monitoring reports of each project, which can be found using the CDM Project Cycle Search (UNFCCC 2015).
2. Project 767 was chosen because it is cited and used convincingly in Schneider (2011). Project 838 was chosen because of its similarities to project 767: both projects started in May 2007, have data available up until November 2010, and have April as the last month in the crediting period.

More generally, one might imagine a plant that is assigned a baseline lower than its emissions pathway—a stringent baseline. This plant might still participate in the CDM because the high profit margins of HFC-23 credits justify reducing emissions without reward. The result is under-credited emissions reductions. Whether plants were assigned baselines that were too low or too high *on average* determines the overall emissions consequences of HFC-23 projects and is the focus of the main paper.

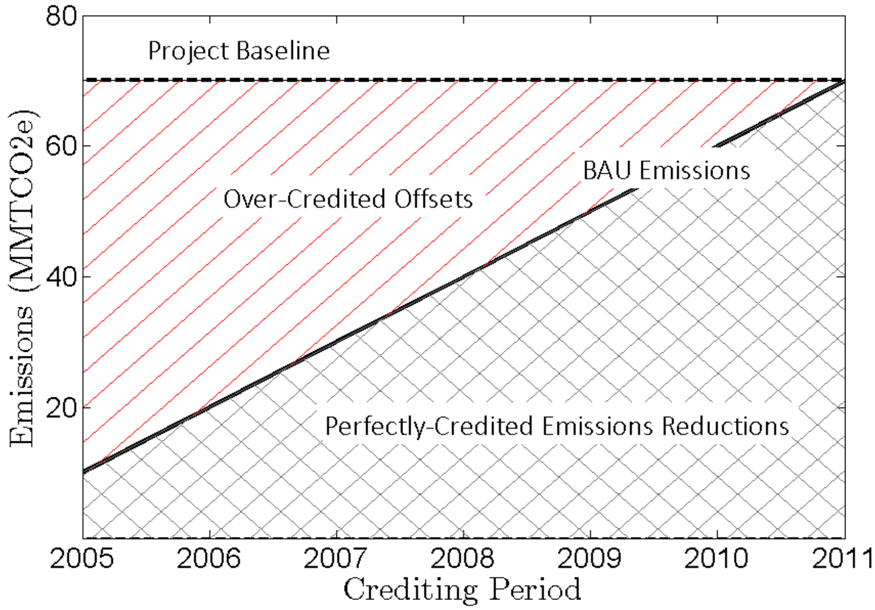
A2. Opt-In Choices with Different Assigned Baselines

Figures A2 and A3 represent the choice of one project to opt in or opt out of the CDM HFC-23 program. In each case, the regulator assigns the project a baseline that determines the plant's potential supply of over-credited offsets, under-credited emissions reductions, and perfectly credited emissions reductions, the last of which rewards an amount of credits exactly equal to the amount of reductions. Given these assigned baselines, plants choose whether to emit zero HFC-23 emissions (a binary emissions choice that reflects installation of thermal oxidation technology) or continue along their BAU emissions path. Assigned baselines are represented as horizontal lines to reflect constant baselines under the HFC-23 methodologies considered in this paper.

In Figure A2, the regulator assigns the project a baseline higher than BAU emissions levels. The project opts in, choosing to emit zero HFC-23 emissions, because it will receive over-credited offsets at no cost without reducing BAU emissions levels. For each crediting period, the project also supplies perfectly credited reductions by reducing emissions below BAU levels.

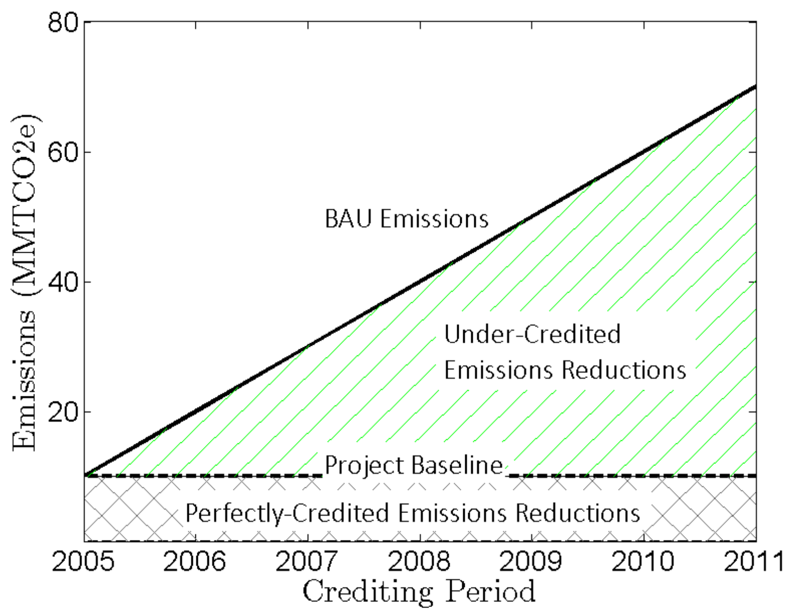
In Figure A3, a regulator assigns a baseline above BAU emissions levels, but the project still chooses to opt in. The project chooses to opt in despite having to reduce emissions from its baseline to its BAU emissions levels without credit. This case is plausible if the reward (marginal revenue) gained from reductions below BAU emissions levels is high enough to justify making reductions for no credit. Such conditions might hold for a significant portion of HFC-23 projects because the cost of reductions (US$0.2 to –$1.0 per ton of CO_2e) compares favorably with the benefits, the market price for a CER, which have traded for US$3 to $20 between 2008 and 2012 (Schneider 2007).

Figure A2. Emissions Choice with High Assigned Baseline



Notes: The project chooses to opt in to the CDM by installing thermal oxidation technology, essentially reducing emissions to zero. The supply of offsets consists of over-credited offsets, which the project received at no cost and are equal to the difference between the project's assigned baseline and BAU emissions, and perfectly credited reductions, which are associated with positive costs.

Figure A3. Emissions Choice with Low Assigned Baseline



Note: The project chooses to opt in to the CDM because the benefits of reducing emissions that are credited are greater than the costs of reducing emissions, from BAU levels to its assigned baseline, that are not credited.

A3. Crediting Supplies and Net Emissions Impact from Individual HFC-23 Projects

Tables A2, A3, and A4 display under-credited emissions reductions and over-credited offsets resulting from our Intermediate BAU HFC-23 emissions scenario and our three cases for assigned baselines: benchmark, perverse incentives, and strong perverse incentives. We created similar sets of tables for the Low and High emissions scenarios but do not report them here.

Table A2. Crediting for HFC-23 Projects under the Intermediate BAU HFC-23 Emissions Scenario: Strong Perverse Incentives (in tons HFC-23)

(a) Under-Credited Emissions Reductions

Project #	2006	2007	2008	2009	2010	2011	2012	2013	Total
11	0	0	0	0	0	0	0	0	0
151	0	0	0	0	0	0	0	0	0
193	400	440	440	440	440	440	440	440	3483
232	N/A	191	191	191	191	191	191	191	1336
306	0	0	0	0	0	0	0	0	0
549	33	48	48	48	48	48	48	48	371
550	N/A	0	0	0	0	0	0	0	0
767	N/A	0	0	0	0	0	0	0	0
868	N/A	66	67	67	67	67	67	67	466
1105	N/A	N/A	0	0	0	0	0	0	0
1194	N/A	0	0	0	0	0	0	0	0
1947	N/A	N/A	N/A	0	0	0	0	0	0

(b) Over-Credited Offsets

Project #	2006	2007	2008	2009	2010	2011	2012	2013	Total
11	271	251	251	251	251	251	251	251	2026
151	182	182	182	182	182	182	182	182	1453
193	0	0	0	0	0	0	0	0	0
232	N/A	0	0	0	0	0	0	0	0
306	270	242	242	242	242	242	242	242	1962
549	0	0	0	0	0	0	0	0	0
550	N/A	109	109	109	109	109	109	109	760
767	N/A	177	177	177	177	177	177	177	1236
868	N/A	0	0	0	0	0	0	0	0
1105	N/A	N/A	111	111	111	111	111	111	668
1194	N/A	8	8	8	8	8	8	8	59
1947	N/A	N/A	N/A	45	45	45	45	45	226

Note: N/A refers to years when a project had yet to commence its crediting period and therefore could not receive any credits.

Table A3. Crediting for HFC-23 Projects under the Intermediate BAU HFC-23 Emissions Scenario: Perverse Incentives (in tons HFC-23)

(a) Under-Credited Emissions Reductions

Project #	2006	2007	2008	2009	2010	2011	2012	2013	Total
11	0	0	0	0	0	0	0	0	0
151	0	0	0	0	0	0	0	0	0
193	400	440	440	440	440	440	440	440	3483
232	N/A	191	191	191	191	191	191	191	1336
306	0	0	0	0	0	0	0	0	0
549	33	48	48	48	48	48	48	48	371
550	N/A	0	0	0	0	0	0	0	0
767	N/A	41	41	41	41	41	41	41	285
868	N/A	66	67	67	67	67	67	67	466
1105	N/A	N/A	0	0	0	0	0	0	0
1194	N/A	0	0	0	0	0	0	0	0
1947	N/A	N/A	N/A	0	0	0	0	0	0

(b) Over-Credited Offsets

Project #	2006	2007	2008	2009	2010	2011	2012	2013	Total
11	271	251	251	251	251	251	251	251	2026
151	34	27	27	27	27	27	27	27	223
193	0	0	0	0	0	0	0	0	0
232	N/A	0	0	0	0	0	0	0	0
306	270	242	242	242	242	242	242	242	1962
549	0	0	0	0	0	0	0	0	0
550	N/A	109	109	109	109	109	109	109	760
767	N/A	0	0	0	0	0	0	0	0
868	N/A	0	0	0	0	0	0	0	0
1105	N/A	N/A	111	111	111	111	111	111	668
1194	N/A	8	8	8	8	8	8	8	59
1947	N/A	N/A	N/A	45	45	45	45	45	226

Note: N/A refers to years when a project had yet to commence its crediting period and therefore could not receive any credits.

Table A4. Crediting for HFC-23 Projects under Intermediate BAU HFC-23 Emissions Scenario: Benchmark (in tons HFC-23)

(a) Under-Credited Emissions Reductions

Project #	2006	2007	2008	2009	2010	2011	2012	2013	Total
11	38	59	59	59	59	59	59	59	449
151	13	19	19	19	19	19	19	19	148
193	79	120	120	120	120	120	120	120	918
232	N/A	132	132	132	132	132	132	132	926
306	53	81	82	82	82	82	82	82	624
549	29	45	45	45	45	45	45	45	346
550	N/A	38	38	38	38	38	38	38	264
767	N/A	27	27	27	27	27	27	27	191
868	N/A	60	60	60	60	60	60	60	419
1105	N/A	N/A	23	23	23	23	23	23	140
1194	N/A	44	44	44	44	44	44	44	311
1947	N/A	N/A	N/A	79	79	79	79	79	393

(b) Over-Credited Offsets

Project #	2006	2007	2008	2009	2010	2011	2012	2013	Total
11	0	0	0	0	0	0	0	0	0
151	0	0	0	0	0	0	0	0	0
193	0	0	0	0	0	0	0	0	0
232	N/A	0	0	0	0	0	0	0	0
306	0	0	0	0	0	0	0	0	0
549	0	0	0	0	0	0	0	0	0
550	N/A	0	0	0	0	0	0	0	0
767	N/A	0	0	0	0	0	0	0	0
868	N/A	0	0	0	0	0	0	0	0
1105	N/A	N/A	0	0	0	0	0	0	0
1194	N/A	0	0	0	0	0	0	0	0
1947	N/A	N/A	N/A	0	0	0	0	0	0

Note: N/A refers to years when a project had yet to commence its crediting period and therefore could not receive any credits.

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