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COSTS OF GREENHOUSE GAS EMISSIONS ABATEMENT UNDER THE CLEAN DEVELOPMENT MECHANISM

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This paper examines the costs of emissions abatement through various types of projects financed under the Clean Development Mechanism (CDM) of the Kyoto Protocol. Using project data, cost functions are estimated applying alternative functional forms. Results show that the average cost of abatement decreases with the volume of abatement, showing economies of scale and suggesting that reducing emissions through small projects is relatively expensive. Results also show significant variation in the costs of abatement by project type and location. Nevertheless, the observed distribution of project investments does not closely match the relative cost structure, either by location or project type. Renewable energy projects accounted for 62% of the projects even though they had the second highest cost. Most of the CDM projects are located in emerging economies, principally China, India, and Brazil, even though the fixed costs of establishing CDM projects in these countries are higher than in many other developing countries. Significantly, while much of the conceptual and applied numerical literature concerning greenhouse gas abatement policies relies on presumptions about the structure of abatement cost curves, these findings suggest that comparative advantage is only one of several factors driving CDM investments and that investors hold additional preferences about project location and project type. Finally, results indicate a general, though noncontinuous, downward trend in the costs of abatement for new CDM projects.

Keywords: Kyoto protocol; CDM projects; greenhouse gas emissions; abatement costs.

JEL Codes: F53, Q54, Q56, Q58

1. Introduction

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) sets binding targets for the European Community and other industrialized countries (i.e., countries listed in Annex B of the Kyoto Protocol) for curbing anthropogenic Greenhouse Gas (GHG) emissions. While Annex B countries are committed to limit GHG emissions to pledged amounts primarily through national measures, the treaty offers three market-based mechanisms intended to lower the cost of abatement: (1) Emissions Trading (ET), (2) Joint Implementation (JI), and (3) the Clean Development Mechanism (CDM).[1] The JI and CDM are two project-based mechanisms that allow Annex B countries to meet their targets by sequestering GHGs or reducing GHGs emissions in other countries. While the JI mechanism enables the Annex B countries to carry out bilateral or multilateral emissions reduction projects among themselves, the CDM encourages investment in sustainable development projects that reduce emissions in developing countries.[2] The ET allows Annex B countries to trade AAUs as well as credits generated by the project-based mechanisms among themselves.[3]

In response to the CDM provision, a large number of emissions reduction projects have been initiated in different developing countries, which widely vary both in the type of abatement technology used and the size of operation. This paper examines the abatement cost structure of the CDM projects in the pipeline with the objective of assessing the cost-effectiveness of GHG reductions through the CDM and providing policy relevant perspectives.

The CDM provides an incentive to Annex B countries for meeting their targets at lower costs. For measurable and verifiable emissions reductions that are additional to what would have occurred without the CDM project, an Annex B country earns certified emission reduction (CER) credits, each equivalent to one ton of CO_2 equivalent (tCO_2e hereafter) abatement. The Annex B country is allowed to use the earned CERs to meet part of its emission reduction targets under the Kyoto Protocol or sell the credits to other parties. Stimulating sustainable development through technology transfer and foreign direct investments, the CDM also provides a way for developing countries to contribute to emissions reduction efforts.

Both industrialized and developing countries have responded to the incentives provided through the CDM. As of December 2010, there were 6700 projects at some stage of the CDM project cycle.[4] If all of these projects were validated by the Executive Board (EB) and implemented to their full potentials, they would generate emissions reductions totaling 3.51 billion tCO_2e and generate an equivalent number of CERs by the end of the first commitment period of the Kyoto Protocol in 2012 (UNEP Risoe CDM/JI Pipeline Analysis and Database, 1 January 2011).

While the rapid increase in the number of CDM projects indicates that this provision aligns the incentives of the Annex B and non-Annex B parties, the role of cost

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[1] Annex B countries have accepted targets for limiting or reducing emissions. These targets are expressed as levels of allowed emissions, or “assigned amounts,” over the 2008–2012 commitment period. The allowed emissions are divided into “assigned amount units” (AAUs).

[2] The JI and CDM are also intended to attract the private sector to contribute to mitigation efforts. According to the JI and CDM pipeline database, most of the projects are private initiatives (UNEP Risoe CDM/JI Pipeline Analysis and Database, 1 November 2008).

[3] As set out in Article 17 of the Kyoto Protocol, Annex B countries with fewer emissions than permitted are allowed to sell the excess AAUs to the countries with more emissions than permitted.

[4] See Larson *et al.* (2008) for a discussion of CDM implementation rules and the CDM project cycle.

as a motive for investment is less well understood. Improving on this understanding is crucial for policy. This is because most numerical analysis of how the CDM affects the cost of meeting the Kyoto Treaty objectives are based on specified abatement cost curves and the assumption that capital will seek out least-cost projects.[5] This same approach also leads to prediction of the sectors and regions likely to benefit from project investment flows. However, project costs are not synonymous with abatement costs and there are additional characteristics that influence project investment decisions. Our results suggest these factors are consequential and explain why the current pool of project investments differs from ex ante predictions.[6]

While previous studies provide useful estimates of abatement costs of various pollutants, a majority of those are based on secondary data or approximated coefficients in the abatement functions. In this paper, we take advantage of available data on CDM projects to answer several questions that are important for the future of CDM policy design but have not been addressed earlier. The project-level data distinguishes among various types of projects, methodologies for calculating emissions reductions, the countries hosting the projects, and sequence of new project investments for the period 2003–2010. Thus, our dataset allows us to draw distinction among projects across types (technologies), methodologies, locations, and time.

These features of the data allow us to examine the relative role of abatement costs in explaining the pool of observed investments. It also allows us to test two hypotheses important for policy: (1) whether CDM projects exhibit economies of scale in emission abatement, and (2) whether the average cost of abatement of CDM projects has decreased over time, presumably due to accumulated experience.

The remainder of the paper is organized in the following way. After selectively reviewing the relevant literature, the following section describes the conceptual model and empirical framework for estimating abatement costs of CDM projects. Section 3 describes the CDM project-specific data. Section 4 delineates the estimation results and discusses the implications. Finally, the last section concludes the paper.

2. Estimating Emissions Abatement Costs of the CDM

One of the early studies on pollution abatement cost was undertaken by Rossi *et al.* (1979). They estimated a cost function in which abatement cost is a function of the volume and quality of both effluent and influent streams and factor prices (i.e., prices of land, labor, capital, and materials). Fraas and Munley (1984) also estimated water pollution abatement costs based on the framework proposed by Rossi *et al.*

Goldar *et al.* (2001) identified problems associated with the cost function proposed by Rossi *et al.*, and argue that output of abatement activity should be defined as the reduction in the pollution load. They define output of water pollution abatement as a

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[5] Metz *et al.* (2007) provide a careful discussion of abatement cost curves in top-down and bottom-up models of mitigation costs and how the models are used to inform policy.

[6] See Rahman *et al.* (2012) for a review of ex ante predictions for the CDM.

function of the volume of waste water treated, the difference in the pollution levels of influent and effluent water, and inputs used to purify the water. Golder *et al.* specified a water pollution abatement cost function in which the cost of abatement is an explicit function of the quantum of abatement (i.e., the difference between water quality before and after the treatment) and factor prices. There are some similar studies that did not include factor prices in the abatement cost function (e.g., Mehta *et al.*, 1993).

Another set of studies considered pollution abatement as an inseparable multi-output process, and suggested that the cost of abatement might not be separable from the cost of production (see Pizer and Kopp, 2005; Maradan and Vassiliev, 2005; Boyd *et al.*, 1996). Gollup and Roberts (1985) used observed data on utility pollution abatement and production costs to estimate a cost function that included emission control rates as a predictor of production costs. Nordhaus (1994) compared a number of published models in terms of percentage difference of carbon emissions from a baseline path and propose an aggregate formula relating cost to output and reduction of GHGs. In a similar manner, Newell and Stavins (2003) explored the pollution abatement cost heterogeneity (i.e., the relative cost of uniform performance measured in terms of emissions per unit of product output) by using a second-order approximation of the costs around the baseline emissions. Their approach was based on variation in baseline emission rates, thus estimation of the cost function required data on baseline and project emissions. In contrast, Newell *et al.* (2003) developed a quadratic abatement cost function in which the cost of pollution abatement per unit of output depends on abatement rather than emissions. Using project-level census data on compliance costs and emissions abatement in four industries, they estimated the parameters of the cost function and compute gains from emission trading.

In their study of power generation and the US SO_2 program, Considine and Larson (2006) considered the use of the atmosphere for the disposal of emissions as a factor of production, priced by tradable emission permits, and derived related input demand schedules in a cost-function framework. The authors applied a similar approach in their paper on the European Union's program for GHGs (Considine and Larson, 2012).

Several studies estimated the abatement cost function by separating cost of abatement from the cost of production. Using data from the US Census Bureau, Hartman *et al.* (1994) estimated air pollution abatement costs by industry sectors. Assuming that the abatement cost function was separable from the firm's production cost function, they estimated abatement costs as a quadratic function of emissions abatement. Hamaide and Boland (2000) defined abatement costs as a second-order polynomial function of abatement alone. While estimating the cost of abating agricultural nitrogen pollution in wetlands, Bystrom (1998) estimated linear, quadratic, and log–log specifications of a cost function.

For the projects that generate CERs only, total project costs are synonymous with abatement costs. However, in some cases, project investments increase power generations as well as mitigate GHG emissions. In this paper, our initial focus will be on a separable cost function; consequently we calculate a net cost of abatement by subtracting out net revenues from the expected sales of electricity, a “by-product” of abatement. Later, we repeat the analysis using total project costs, but include expected power increases as a control.

Finally, before proceeding to the empirical model, it is worth noting that we have been careful not to ascribe additional features regarding the benefits or costs of the projects outside of those arising under the CDM project chain. In particular, the environmental benefits of the projects are exclusively measured in terms of expected mitigation benefits, measured in CERs, even though they may generate other externalities, positive or negative. We also uniformly stick with the CDM Boards projections of expected CERS, even though known risks are likely higher for some projects, which should in turn affect their pricing. We also do distinguish among the underlying baseline assessments, even though most researchers would draw sharp distinction as to the reliability of the many CDM approved baseline technologies. To illustrate, community-based land restoration projects may well generate significant co-benefits by improving fresh water catchments, restoring land fertility, and generating additional income for the rural poor. At the same time, the carbon sequestration benefits they generate are difficult to measure and subject to reversal. Because they often rely on the actions of many households and communities, they are also more susceptible to co-ordination failures (Larson *et al.*, 2011).

2.1. *The conceptual model*

As a starting point for the derivation of our applied model, consider the expected project value function, where the value of the investment, V_0, is determined by the discounted value of two streams of profit from a project initiated in year 0 and expected to last n years[7]:

$$V_0 = \sum_0^n \pi_t^A e^{-rt} + \sum_0^n \pi_t^E e^{-rt}; \quad t = 1, 2, \ldots, n, \tag{1}$$

where the superscripts A and E distinguish between the expected profits from producing abatement credits and profits from generating electricity. The equation can be expanded to distinguish revenues from costs:

$$\sum_0^n \pi_t^A e^{-rt} + \sum_0^n \pi_t^E e^{-rt} = \sum_0^n p_t^A A_t e^{-rt} + \sum_0^n p_t^E E_t e^{-rt} - C_0^J. \tag{2}$$

For the moment, we treat the costs of producing both abatement credits and electricity as joint, and denote the total discounted costs as: $C_0^J = I_0 + \sum_0^n c_t e^{-rt}$, where c is the annual variable cost of the project. When the rate of expected profit clears the investment hurdle, positive investments are observed and the associated value function

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[7] See Timilsina and Lefevre (1999) for a related discussion.

can be characterized as:

$$V(I_0^*) = \bar{p}_0^A \sum_0^n A_t e^{-rt} + \bar{p}_0^E \sum_0^n E_t e^{-rt} - C^J(A_0, E_0), \tag{3}$$

where the $\bar{p}_0^A$ and $\bar{p}_0^E$ represent the weighted average prices for abatement and power at the time the investment decision is made. The aggregate output levels consistent with solution values can be recovered via the envelope theorem, as: $\frac{\partial I^*}{\partial \bar{p}_0^A} = \sum_0^n A_t e^{-rt} \equiv A_0$ and $\frac{\partial I^*}{\partial \bar{p}_0^E} = \sum_0^n E_t e^{-rt} \equiv E_0$, where A_0 and E_0 are the volumes of CERs and of electricity that the project is expected to produce over its lifetime, weighted by the discount factor used in the evaluation of the investment function.

The associated joint cost function can be written as:

$$C_\tau^J(w_\tau, A_\tau E_\tau; S_\tau), \tag{4}$$

where τ is the initial period of a given project, where w_τ is the vector of expected input prices, and S_τ is the set of state variables, in addition to input prices, that conditioning the optimization problem.

The problem can be simplified when costs are not joint, that is, when $C^J = C^A(A) + C^E(E)$. In this case, Eq. (3) can be restated as:

$$V(I_c^*) = V(I_0^*) - \sum_0^n p_t^E E_t e^{-rt} = \bar{p}_0^A \sum_0^n A_t e^{-rt} - C^A(A_0) - C^E(E_0), \tag{5}$$

where, as before, the optimal level of abatement can be recovered via the envelope theorem. However, in this case we need not keep track of the optimal level of power generated by the project, since our objective is to estimate the abatement portion of the nonjoint cost function, given by:

$$C_\tau^A(w_t, A_\tau; S_\tau), \tag{6}$$

where $C_0^A = I_0 - \sum_0^n p_t^E E_t e^{-rt} + \sum_0^n c_t^A e^{-rt}$ and where c_t^A are the variable costs associated with abatement.

2.2. *The empirical emissions abatement cost function*

Assuming fixed input prices, the basic expressions for the log–log and log–quadratic functional forms of the abatement cost for project *i* can be given by:

$$\ln(C_i) = \alpha + \beta \ln(A_i) + \theta q_i \quad \text{and} \tag{7}$$

$$\ln(C_i) = \alpha + \beta \ln(A_i) + \gamma[\ln(A_i)]^2 + \theta q_i, \tag{8}$$

where C is the net present value of total abatement costs, A is total emissions abatement, q is a vector of control variables (e.g., project duration, project types, and location), and α, β, γ, and θ are parameters to be estimated.[8] Equation (7) is nested in

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[8] In the current setting, we suppress the time subscript assuming that the equilibrium level of abatement would be the same in each year. This restriction is consistent with the CDM pipeline dataset in which expected emissions abatement and investments are annualized based on the PDDs. We expect to relax this assumption in future work when data on actual abatement and investments are available.

(8) and the two are indistinguishable when γ is indistinguishable from zero. Given the parameter estimates, the marginal cost of abatement can be computed for different types of CDM projects corresponding to Eqs. (7) and (8) by $\frac{\partial C}{\partial A} = \beta \frac{C}{A}$ and $\frac{\partial C}{\partial A} = (\beta + 2\gamma)\frac{C}{A}$, respectively.

The vector of input prices, w, associated with the cost functions is not always observed; however, for a given time period and a given location, the prices of the inputs are likely the same. Thus, dummy variables for different project types, location, and time periods can be used as a proxy for the missing input price vector. Said more formally, let x_m be the vector of inputs associated with a specific abatement methodology, for example generating solar power. The associated vector of prices can vary by time (t) and place (l), suggesting the notation $w_{x,l,t}$. Because we lack specific information about this vector, we use a triplet of dummies (x, l, t) to proxy the missing input prices. This solves the missing price information problem, but the associated parameter on the indicator variables likely pick up other attributes of time and place. This is a mixed blessing, since the net effect is to round up otherwise unobserved effects; however, it does confound the interpretation of the estimated fixed effects.

Separate from differences in costs and expectations explained by start-dates of the projects, the duration of the projects may also matter. In general, the cost of emissions abatement should be lower for the CDM projects with longer duration than the projects of same size and type with shorter duration as time constraint is relaxed in the former. However, projects with longer duration are likely to be riskier as well. In order to take account of such time relationships, project duration (in years) is also used as a continuous explanatory variable.

3. Data Description

Available information about CDM projects sent to the CDM EB for consideration through December 2010 are obtained from the CDM/JI Pipeline Analysis and Database of the United Nations Environment Programme (UNEP) Risoe Center. The dataset includes information about individual CDM project, including the project name, type, registration or validation status, approved methodologies for calculating emissions reductions, involved host countries and credit buyers, expected CERs, and power generation capacity. While information about inputs used in the projects are not available, the technology employed for each project is laid out in the baseline documentation of CDM projects and therefore implicitly in the project classifications, which are based on applied baseline technologies.

Scrutiny of the dataset shows that the CDM portfolio has grown rapidly since its inception in 2003. By December 2010, 6977 CDM projects have been sent to UNFCCC for validation. 1079 of these projects have been registered, 351 are in the process of review, 5270 are in the process of validation, while 226 projects were either withdrawn or rejected by the CDM EB or terminated by independent Designated

Operational Entities (DOE) upon audit (UNEP Risoe CDM/JI Pipeline Analysis and Database, 1 January 2011). Moreover, there are 49 observations with missing abatement data and two observations with zero abatement. The remaining 6700 CDM projects in the pipeline are expected to reduce approximately 872.47 Million tCO_2e per year and a total of 3.51 billion tCO_2e by the period ending in 2012.

Following the UNEP Risoe Center Protocol, the CDM projects in the pipeline can be categorized into eight major types: (1) renewable resource based, (2) methane avoidance, coal bed/mine and cement, (3) supply-side energy efficiency, (4) demand-side energy efficiency, (5) hydrofluorocarbon (HFC), perfluorocarbon (PFC), and nitrous oxide (N_2O) reduction (H/PFCs and N_2O reduction hereafter), (6) fossil fuel switch, (7) forestation, and (8) transport. The CDM board has approved 115 different methodologies to calculate emissions reductions by these projects. The methodologies account for the type of technologies employed by the projects. Given the size of the project, a specific methodology or a combination of two or three relevant methodologies is used to calculate emissions reduction. While different methodologies are used to calculate emissions reduction by different project types, some common methodologies are used to evaluate emissions reduction by different types of projects. However, approved methodologies[9] can be categorized in six major groups: (1) large scale (AM), (2) large scale consolidated (ACM), (3) small scale (AMS), (4) large scale afforestation and reforestation (AR-AM), (5) large scale consolidated afforestation and reforestation (AR-ACM), and (6) small scale afforestation and reforestation (AR-AMS). Note that 'scale' is a measure of project size that has changed over time; small scale methodologies are limited to small projects and are much cheaper and quicker to implement. Table 1 reports the number and percentage of the CDM projects in the pipeline and annual and total CERs to be generated by the end of the first commitment period by each major project type and methodology.

As can be seen from Table 1, about 62% of the projects in the CDM pipeline are renewable resource-based power generating projects accounting for 44% and 38% of the annual and total abatement during the first commitment period, respectively. Methane avoidance, coal bed/mine and cement is the second largest category in terms of number (17%) and annual abatement (18%), but HFCs, PFCs, and N_2O reduction is the second largest category in terms of 2012 abatement (23%). Transport is the smallest and forestation is the second smallest category in terms of both number of projects and abatement. Large scale methodologies (AM) are applied to 7% of the projects, which account for 27% of the total annual abatement by the projects in the pipeline. Large scale consolidated (ACM) and small scale (AMS) methodologies are applied to 46% and 46% of the projects that account for 62% and 10% of annual abatement, respectively.

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[9] For explanation of approved CDM methodologies see http://cdmpipeline.org/cdm-methodologies.htm.

Table 1. Major types of CDM projects in the pipeline — number and emissions abatement.

	Number of projects		Annual abatement		Abatement by 2012	
	Number	% total	$KtCO_2e$	% total	$KtCO_2e$	% total
Project type						
Renewable resource-based	4,181	62.40	380,795	43.65	1,321,041	37.67
Methane, coal mine, etc.	1,142	17.04	159,812	18.32	700,088	19.96
Supply-side energy eff.	689	10.28	120,065	13.76	391,855	11.17
Demand-side energy eff.	301	4.49	11,976	1.37	46,327	1.32
Fossil fuel switch	170	2.54	52,637	6.03	223,290	6.37
HFCs, PFCs, and N_2O	116	1.73	138,099	15.83	792,811	22.61
Forest	66	0.99	5,547	0.64	21,051	0.60
Transport	35	0.52	3,543	0.41	10,467	0.30
Total	6,700	100.00	872,473	100.00	3,506,930	100.00
Methodology						
Large scale (AM)	460	6.87	236,546	27.11	1,167,651	33.30
Large scale consol. (ACM)	3,080	45.97	542,307	62.16	1,958,857	55.86
Small scale (AMS)	3,094	46.18	88,073	10.09	359,371	10.25
Afforest. and reforestation	66	0.99	5,547	0.64	21,051	0.60
Large scale (AR-AM)	25	0.37	4,469	0.51	16,202	0.46
Large sc. con. (AR-ACM)	14	0.21	892	0.10	3,913	0.11
Small scale (AR- AMS)	27	0.40	186	0.02	936	0.03
Total	6,700	100.00	872,473	100.00	3,506,930	100.00

Source: UNEP Risoe CDM/JI Pipeline Analysis and Database (2008), Available at http://cdmpipeline.org/.

Following UNEP Risoe Center, the expected issuance of CERs for each individual project in each year over the life of the project is calculated by adjusting the annual average emissions abatement with an increment or decrement as reported in the database.[10] The crediting period is either 20 or 30 years for the afforestation and reforestation projects and either seven or 10 years for all other types of projects. We consider the number of credit years as the duration of the project. In addition to CERs, some projects generate additional electricity output (in addition to the capacity of the baseline). The pipeline database reports the additional electricity generation capacity and expected hours of operation for individual projects. Using this data, the expected electricity output measured in megawatt hours (MWh) are calculated for each year of the project.

Individual CDM projects widely vary across types in terms of expected annual average CERs and electricity output. The smallest project in the CDM pipeline is

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[10] The CDM pipeline database reports the annual increment or decrement in a variable namely ‘slope.’ The expected CER issuance over the life of a project is approximated with a straight line that goes through the annual average value in the mid-year. For a positive (negative) value of ‘slope,’ expected CERs increases (decreases) each year by the ‘slope’ amount. There is no change in expected CERs over time when ‘slope’ is zero.

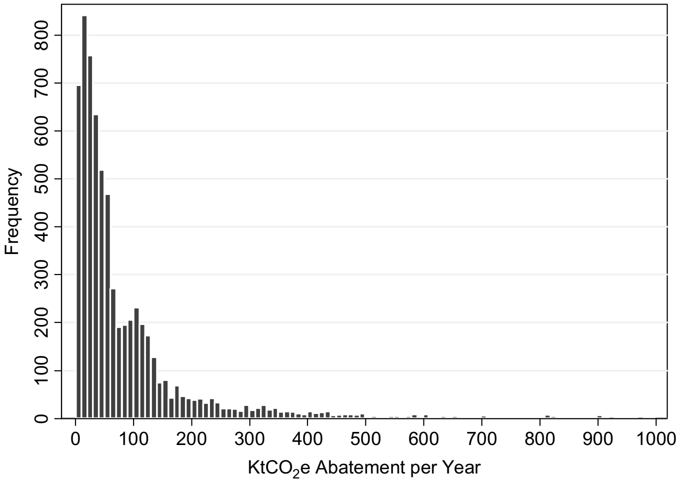

Figure 1. Frequency distribution of the CDM projects by size (KtCO_2e abatement per year)

expected to generate only 400 CERs per year, while the largest project is expected to generate more than 10.4 million CERs per year. The median and mean of annual expected CERs from the projects are 49,000 and 130,220, respectively. Figure 1 shows the frequency distribution of the CDM projects within each capacity interval of 10,000 CERs per year. In terms of expected total CERs, the size of individual projects ranges from 3500 to 836.2 million, with a median at 0.4 million and mean at 1.1 million CERs.

Table 2 shows the mean and range of annual expected CERs and electricity generation by various types of CDM projects in the pipeline. In terms of average annual expected CERs, H/PFCs and N_2O reduction projects are the largest and demand-size energy efficiency projects are the smallest among the major categories. Fossil fuel switch is the second largest category while forest is the second smallest category. Renewable resource-based project category ranks sixth in terms of average annual expected CERs.

Emissions reduction is the sole purpose of the H/PFCs and N_2O reduction, forest, and transport projects. After excluding these categories, electricity generation is a joint purpose of 72% of the CDM projects in the remaining categories. While the average additional electricity generation capacity of these projects is about 206,000 MWh per year, the capacity ranges from 10.0 to 29.8 million MWh (Table 2). In terms of total electricity generation per year, renewable resource-based is the largest category, followed by supply-side energy efficiency, fossil fuel switch, demand-side energy efficiency, and methane avoidance, respectively. More than 91% of the renewable resource-based, 80%of the supply-side energy efficiency, and 44% of the fossil fuel switch projects are capable of generating electricity.

The UNEP Risoe Center reports initial capital investments in 4,418 of the projects in the pipeline. Annual operation and maintenance cost data for 122 projects are

Table 2. Annual abatement and electricity generation by different types of CDM projects.

Project type	Annual abatement ($KtCO_2e$)				Annual electricity output (MWh)			
	Obs.	Mean	Min	Max	Obs.	Mean	Min	Max
Renewable resource-based	4,181	91	0.5	4,334	3,819	119,443	10	5,340,000
Methane, coal mine, etc.	1,142	140	1.0	8,362	378	41,037	141	1,139,500
Supply-side energy eff.	689	174	0.9	3,746	555	661,468	13	29,800,000
Demand-side energy eff.	301	40	0.7	852	16	72,483	7,912	189,214
Fossil fuel switch	170	310	1.1	3,190	74	2,114,566	24,600	9,157,131
HFCs, PFCs, and N_2O	116	1,191	8.0	10,437	—	—	—	—
Forest	66	84	0.4	2,036	—	—	—	—
Transport	35	101	2.8	583	—	—	—	—
Total	6,700	130	0.4	10,437	4,842	205,786	10	29,800,000

Source: UNEP Risoe CDM/JI Pipeline Analysis and Database (2008), Available at http://cdmpipeline.org/.

obtained from the PDDs through collaboration between Climate Solutions and the World Bank in 2008.[11] Using the available costs data, initial investment and operation and maintenance costs per unit of $KtCO_2e$ abatement are calculated. Average per unit capital costs and operation and maintenance cost of abatement across the CDM projects, categorized by project sub-types, are calculated and then used as proxies for the projects for which such data were not available.

The present value of emissions abatement costs for each project are calculated as described in Eq. (6). The operation and maintenance costs are discounted using real interest rates for the year of fixed capital investment (i.e., the prior year of credit start period). Real interest rates in the host countries are used for unilateral projects, while the rates in the partner countries are used for bi- and multi-lateral projects. Real interest rates for the host and partner countries are obtained from the World Bank (WDI, 2010). For the electricity generating CDM projects, the net present value of emissions abatement costs are calculated by subtracting the sum of the discounted flow of electricity sales revenue from the present value of total costs. Wholesale electricity tariffs in different host countries obtained from the PDDs are used to calculate the flow of revenues from electricity sales. Real interest rates are used to discount those revenues.

As implied by duality, the abatement cost function includes the sum of the discounted-weighted flows of CERs and electricity outputs. Real interest rates as mentioned above are used to discount those streams of outputs. Table 3 presents the categorical means and standard deviations of the (discounted) total amount of emissions abatement and electricity outputs over the life of the projects and net present value of total abatement costs of the projects, for which all information are available.

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[11] The operation and maintenance costs data are proprietary and not publicly available. See Annex I in Rahman *et al.* (2012) for details on how operation and maintenance cost were obtained.

Table 3. Net present costs of abatement and discounted total abatement and electricity outputs over the life of the projects.

	No. of obs.	Net present costs (Mill.US$)		Disc. abatement ($MtCO_2e$)		Disc. electricity output (GWh)	
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Renewable resource-based	3,918	122.7	201.5	602.7	1,173.1	668.0	1,505.0
Methane, coal mine, etc.	1,131	72.4	209.4	1,020.9	2,533.1	87.0	315.0
Supply-side energy eff.	637	115.3	253.5	1,074.2	2,018.0	896.1	1,728.6
Demand-side energy eff.	301	56.4	125.1	297.2	618.2	34.0	172.8
Fossil fuel switch	122	71.0	107.2	1,737.4	3,271.1	3,445.7	8,632.6
HFCs, PFCs, and N_2O	116	108.4	214.9	7,712.8	14,701.9	—	—
Forest	66	568.0	1,794.5	1,466.2	4,389.9	—	—
Transport	35	237.6	329.9	734.0	987.1	—	—
Total	6,326	113.8	278.7	872.4	2,776.6	587.6	1,841.3

Source: UNEP Risoe CDM/JI Pipeline Analysis and Database (2008), Available at http://cdmpipeline.org/ .

Wholesale electricity tariffs in some of the host countries were not available, leaving 6326 observations for use in the empirical analyses.

4. Estimation Results and Discussion

The log-transformed net present values of the total cost of abatement by each individual CDM project are plotted against corresponding total abatement and presented in Fig. 2.[12] We estimate the abatement cost first employing the log–log model in Eq. (7), and then examine the more flexible log–quadratic functional form in Eq. (8) with alternative specifications. For analytical convenience, we run the regressions without the intercept terms. To make comparisons easier, we report estimated elasticities or, in the case of the discrete regressors, semi-elasticities (i.e., associated discrete percentage changes in abatement costs as the value of the indicator variable switches from 0 to 1) in the resultant set of tables.

We begin with an ordinary least squares estimation of the log–log model. In particular, the logarithm of abatement cost is regressed on the logarithm of the volume of abatement, logarithm of project duration, and indicator variables for major project types, emissions reduction credit start years, and broad geographical regions (model I). Eight binary variables are used to indicate major project types as described earlier. Ten indicator variables for different credit start years are used; eight for each year during 2005–2012, one for years prior to 2005, and the other for years after 2012. Since the Kyoto Protocol was ratified in 2005, projects for which credit starts prior to year 2005

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[12] Plots of costs against abatement levels for specific project types show a similar pattern.

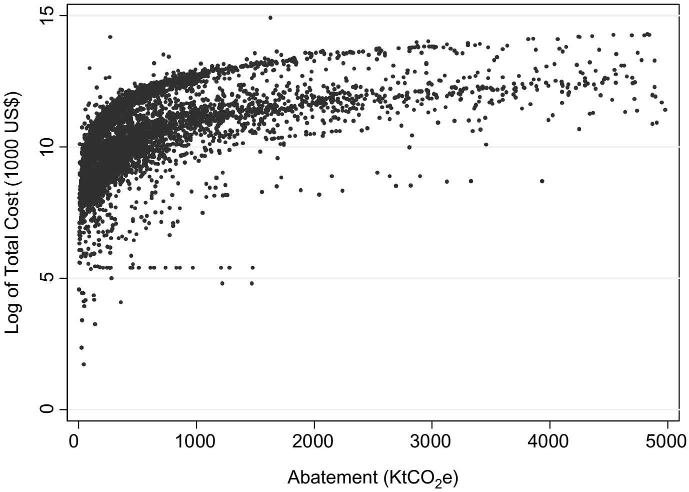

Figure 2. Log-transformed total cost of abatement

are grouped together. In the same fashion, projects for which credit starts after the first commitment period (i.e., after 2012) are categorized in a separate group. Five indicator variables are used for the projects located in Africa, Asia and the Pacific, Europe and Central Asia, Latin America, and the Middle East regions. The estimation results for model I are presented in the second column of Table 4.[13]

For model I, the estimated coefficient of log of abatement (i.e., abatement elasticity) is positive and significant, suggesting that the cost of abatement increases with the volume of abatement (Table 4). A one-tailed test indicates that the elasticity is less than one at 5% significance level, implying 'economies of scale' whereby cost increases proportionately slower than output.[14] Thus, all things equal, larger projects have lower per unit costs. This result implies that small CDM projects should be avoided or consolidated, because those are too costly.

Estimated coefficient of log of project duration is positive and significant (Table 4). This result implies that, all things equal, projects with longer duration have higher per unit cost of abatement. A one-tailed test indicates that the elasticity is not different from one at standard critical levels. Thus, all things equal, abatement cost increases with project duration at the same proportion. The magnitude of the duration effect, however, appears to be much smaller when specific methodology and project location are included in the model (results will follow).

Estimated coefficients of the variables indicating project types are positive and significant at standard critical levels, except for H/PFCs and N_2O reduction projects

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[13] Estimated coefficients and their standard errors under each model are reported in Table A.1.

[14] This test and subsequent ones are one-tailed tests based on a nonlinear combination of estimated parameters and implemented using Stata's (2012) NLCOM post-estimation procedure.

Table 4. Aggregate model results — elasticities and discrete-change effects.

	Log–log: I	Log–quad.: II	Log–quad.: III	Log–quad: IV
Elasticities				
Abatement ($KtCO_2e$)	0.900***	0.897***	0.792***	0.854***
Project duration (years)	0.952**	0.950**	1.087***	0.363*
Discrete-change effects				
Project-type				
Renewable resource	4.032***	4.645***	5.084***	4.957***
HFCs, PFCs, and N_2O	1.722	2.244**	2.610***	2.318***
Methane avoidance	3.149**	3.759***	4.214***	3.927***
Supply-side energy eff.	3.537***	4.148***	4.486***	4.128***
Demand-side energy eff.	4.064***	4.661***	5.145***	4.488***
Fossil fuel switch	3.177**	3.750***	4.215***	3.598***
Transportation	4.720***	5.336***	5.747***	3.850***
Forest	3.972**	4.570***	6.046***	6.395***
Methodology-type				
Large scale consolidated: ACM (dropped)				
Large scale: AM			0.093*	
Small scale: AMS			−0.421***	
AR large scale cons.: AR-ACM			−1.344	
AR large scale: AR-AM			−1.063	
AR small scale: AR-AMS			−1.730***	
Credit start-year				
Prior to 2005 (dropped)				
2005	−0.455	−0.447	−0.419**	−0.132
2006	−0.337	−0.337	−0.282***	−0.039
2007	−0.120***	−0.113**	−0.044	−0.001
2008	−0.293***	−0.279**	−0.210***	−0.133
2009	−0.288***	−0.272***	−0.202***	−0.066
2010	−0.14	−0.128	−0.06	0.102
2011	−0.058	−0.046	−0.011	0.178
2012	−0.381**	−0.371**	−0.344***	−0.139
Post 2012	−0.528*	−0.593**	−0.477	−0.277
Regions				
Africa (dropped)				
Asia and Pacific	−0.247***	−0.241***	−0.248***	
Europe and central Asia	−0.395**	−0.402**	−0.454***	
Latin America	−0.135	−0.139	−0.211***	
Middle East	−0.014	0.011	−0.054	
Host country fixed effects	No	No	No	Yes
Methodology fixed effects	No	No	No	Yes
Observations	6,326	6,326	6,326	6,326
Adjusted R-squared	0.991	0.991	0.991	0.993

Note: Host-country and methodology fixed effects used to estimate model IV are suppressed to conserve space. Underlying parameter estimates are given in Table A.1. Asterisks ***, **, and * indicate significance at 1%, 5%, and 10% levels. The results of separate one-tailed tests indicate that the estimated abatement elasticities are less than 1.00 at 5% significance level for model I, 10% significance level for model II, and, 1% significance level for models III and IV.

(Table 4). The estimated coefficient of the indicator variable for each project type can be interpreted as the conditional expected mean of log of fixed costs of abatement through that type. One-tailed tests for pairwise comparison of the project-type coefficients indicate that the fixed costs for transportation projects is the highest, followed by demand-side energy efficiency (or renewable energy or forest), supply-side energy efficiency, fossil fuel switch (or methane avoidance), and H/PFCs and N_2O reduction projects in a descending order (Stata, 2012).[15]

In the log scale, the difference between the estimates for two different project types is equal to the difference in the expected geometric means of the log of fixed costs for those project types. The exponential of the difference between the two estimates provides the percentage change in abatement cost for switching from one type to the other type of CDM projects. For example, according to the results of model I, the fixed cost of abatement decreases by nearly 41% for switching from demand-side energy efficiency to supply-side energy efficiency projects, holding other variables constant.[16]

The coefficient estimates for all variables indicating credit start years are negative, but significant at standard critical levels only for years 2007–2009, 2012, and later (Table 4). While a continuous downward trend is not obvious from the estimated coefficients of the time dummies, an upward trend can be ruled out.

Estimated coefficients of the variables indicating regions are negative, but significant at standard critical levels only for Asia and the Pacific and Europe and Central Asia (Table 4). Based on these estimates, abatement costs are lower for CDM projects located in Asia and the Pacific and Europe and Central Asia compared to that of Africa, Latin America, and the Middle East. Consistent with this result, most of the projects are situated in Asia.

To allow the cost function to have a more flexible functional form, we estimate emissions abatement costs with a log–quadratic specification. In particular, the log of abatement cost is regressed on the same set of explanatory variables as in model I and squared log of abatement. Estimated elasticities and semi-elasticities for model II are presented in the third column of Table 4. The inclusion of the squared log of abatement as an additional explanatory variable to those in model I does not change the results significantly (see the results for models I and II in Table 4 and Table A.1). While the magnitude of the estimates from models I and II are slightly different, the estimates for each variable has the same sign and level of significance in both models. The estimated coefficient for the squared log of abatement does not appear to be significant in model II (see Table A.1). Thus, log–log and log–quadratic models provide similar estimates.

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[15] One-tailed tests for pairwise comparison of the project-type coefficients indicate that the fixed costs for demand-side energy efficiency, renewable energy, and forest projects are not statistically significantly different from each other. The tests also indicate that the fixed costs for fossil fuel switch and methane avoidance projects are not statistically significantly different from each other.

[16] The percentage change in the geometric mean of the abatement cost for switching from demand-side to supply-side energy efficiency projects is calculated as $100 \times$ [exp(the coefficient for demand-side $-$ the coefficient for supply-side) $- 1$].

To take account of the effect of technology used by the projects on abatement costs, the log of abatement cost is regressed on the same set of explanatory variables as in model II plus a set of indicator variables for major groups of approved methodologies (model III). Estimated elasticities and semi-elasticities for model III are presented in the fourth column of Table 4. The results show that inclusion of indicator variables for categorized methodologies alters the magnitude of the coefficient estimates and corresponding elasticities and semi-elasticities without affecting the signs. The estimated coefficient of the indicator variable for the large scale methodology group (AM) is positive and significant while the coefficients of the indicator variables for all other categories of methodologies are negative and significant at standard critical levels (Table 4). This result suggests that, relative to the large-scale consolidated methodologies (ACM), fixed costs of abatement are higher for large-scale methodologies (AM) and lower for small-scale methodologies (AMS) and all types of methodologies used for afforestation and reforestation projects (AR-ACM, AR-AM, AR-AMS).

As the methodology dummies take account of the fixed effects of various technologies on abatement costs, the coefficient estimates of project type dummies have changed substantially. Forest projects appear to have the highest fixed costs while the order of fixed costs of other project types remains the same as in models (I) and (II). In contrast to the results of models (I) and (II), estimated coefficients for credit start years 2005–2006 appear to be significant, and the coefficient for 2007 does not appear to be significant, while the signs of other coefficients remain the same.

To further investigate the effects of individual methodologies and location of the projects on costs, the log of abatement cost is regressed on the same set of explanatory variables as in model III, except that indicator variables for each specific methodology and host country are used instead of indicator variables for categorized methodology and regions, respectively (model IV). In particular, indicator variables for 86 host countries and 206 methodologies are used.[17] Estimated elasticities and semi-elasticities for model IV are presented in the last column of Table 4.[18] In contrast to the results of other models, the estimated elasticity for project duration is much lower and significantly less than one and none of the coefficients of the indicator variables for credit start years appears to be significant in model IV (Table 4). Thus, some of the duration and timing effects in model (I) are due to project technology and location. The estimated abatement elasticity is significantly less than one and coefficients of project type dummies remains to be positive and significant as in other models. According to the estimated coefficients for project-type dummies in model IV, the fixed cost of abatement is the highest for afforestation and reforestation projects, descending orderly

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[17] While there are 115 distinct methodologies, combination of two or more methodologies are used to calculate mitigation by many projects.

[18] The coefficient estimates of the indicator variables for individual methodologies and host countries in model IV are not presented to conserve space.

followed by renewable resource based, demand-side energy efficiency, supply-side energy efficiency, methane avoidance, transportation, fossil fuel switch, and H/PFCs and N_2O reduction projects. Notably, the distribution of the CDM projects in the pipeline does not quite follow this relative cost structure (recall Table 1).

The estimated coefficients for methodology dummies do not indicate any systematic pattern for different categories, but do indicate significant variations among specific methodologies within each category. The estimates for large-scale (AM) methodologies vary from -2.69 to 2.01, estimates for large-scale consolidated (AMC) methodologies vary from -1.89 to 1.97, the estimates for small scale methodologies (AMS) vary from -1.33 to 1.91, and the estimates for afforestation and reforestation methodologies (AR) vary from -2.12 to -0.27.

The estimated coefficients of the variables indicating different host countries range from -0.86 to 1.82, without any specificity for regions. While these coefficients reflect country-specific fixed costs of abatement, the countries that host the most projects are not the ones that have the lowest-valued country dummies when we include them. Figure 3 depicts the total number of CDM projects in individual host countries against the values of the coefficients for country dummies from model (IV).

In summary, the estimates of models I–IV suggest that the average cost of abatement decreases with the volume of abatement (economies of scale), increases with the duration of the projects, and there is a downward trend (not continuous though) in abatement costs for the new flows of projects. Fixed costs of abatement vary depending on the type and location of the projects. However, the distribution of different types of projects, in the CDM pipeline or across countries, is not consistent with the relative cost structure. This calls for further investigation of the project-type specific and location specific abatement cost structures.

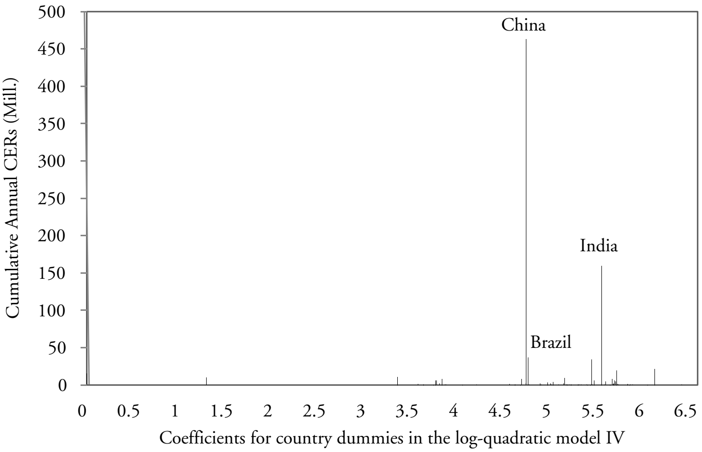

Figure 3. The coefficients of country dummies from model IV and total number of CDM projects in individual host countries

Table 5. Results from project-type analysis — elasticities and discrete-change effects.

	Renewable resource	H/PFCs N_2O	Methane avoid.	Supply-side EE	Demand-side EE	Fossil fuel	Transport	Afforest reforest
Elasticities								
Abatement	0.82***	0.56***	0.93***	0.97***	0.95***	0.82***	0.81*	0.90***
Project duration	0.26***	−0.98	−0.03	0.05	−0.11	−0.41*	−0.50	−0.08
Discrete-change effects								
Dominant methodology								
Large scale con.: ACM 1 (dropped)								
Large scale con.: ACM 2	**0.07****	—	—	5.78***	—	—	—	—
Large scale con.: ACM 12	1.84***	—	—	**5.34****	5.91***	—	—	—
Large scale: AM 34	—	**1.99*****	—	—	—	—	—	—
Small scale: AMS-II.D.	1.09***	—	0.01	5.55***	**6.24*****	0.07	—	—
Small scale: AMS-III.B.	0.99	—	—	—	6.25***	**−0.30**	—	—
Small scale: AMS-III.C.	—	—	—	—	—	—	**−0.15****	—
Small scale: AMS-III.D.	−0.52***	—	**0.38*****	—	6.26***	—	—	—
AR small: AR-AMS1	—	—	—	—	—	—	—	**5.92*****
Credit start-year								
Prior to 2005 (dropped)								
2005	−0.14	−0.07	−0.65*	0.14	0.22***	−0.44	—	—
2006	0.08***	−0.55	−0.24	0.04	−0.05*	0.14	0.13	−0.32*
2007	−0.05	−0.33*	−0.12	−0.16*	−0.02*	0.05	−0.09	−0.33
2008	−0.28	−0.01	−0.13	−0.16	−0.07***	−0.09	−0.15	−0.17
2009	−0.15	−0.28	−0.13	−0.13	−0.05***	−0.52	0.20	−0.19
2010	0.06	0.54	−0.12	−0.12**	−0.05***	−0.25	0.17	−0.03
2011	0.18	0.24	−0.07	−0.14	0.04	0.03	−0.12	1.11**
2012	−0.39	2.97*	0.12	−0.17*	0.40	—	—	—
Post 2012	−0.24	—	−0.15	−2.45***	—	—	7.72	—

Table 5. (*Continued*)

	Renewable resource	H/PFCs N_2O	Methane avoid.	Supply-side EE	Demand-side EE	Fossil fuel	Transport	Afforest reforest
Selected host countries								
Albania (dropped)								
Brazil	5.34***	3.94	5.64***	0.76***	1.09***	6.962***	—	−0.17
China	4.93***	4.029	5.19***	0.05**	0.26***	6.846***	6.61	0.2
India	5.78***	3.668	5.21***	0.02	0.58***	6.611***	7.83	0.15
Mexico	5.69***	3.149	4.51***	0.35***	0.46***	—	6.79	—
Malaysia	5.33***	0	5.05***	−0.35	0.27***	—	—	—
Host country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Methodology fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,919	116	1,129	636	301	120	35	68
Adj. R-squared	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Note: Only the major host-country and dominant (most frequently used) methodology fixed effects are reported while the rest are suppressed to conserve space. Underlying parameter estimates are given in Table A.2. Asterisks ***, **, and * indicate significance at 1%, 5%, and 10% levels. Highlighted estimates for methodology dummies indicate the dominant methodology for each project type. The results of separate one-tailed tests indicate that the estimated abatement elasticities less than one at 1% significance level for renewable resource-based, demand-side energy efficiency, and fossil fuel projects; at 5% significance level for H/PFCs and N_2O reduction projects; and at 10% significance level for afforestation and reforestation projects. The abatement elasticities for other types are not significantly different from 1.00.

Abatement costs for different project types

We examine the abatement cost structure of each project type separately, employing the log–quadratic model with indicator variables for each methodology, credit start year, and host country as in model IV. The elasticity and semi-elasticity estimates are presented in Table 5, and the coefficient estimates with standard errors are reported in Table A.2. To conserve space, only the discrete-change effects for the dominant (most frequently used) methodology in each project category (indicated by highlighted estimates) and the largest five host countries are presented in the tables.

For each project type, the coefficient estimate of log of abatement is positive and significant, suggesting that the cost of abatement increases with the volume of abatement. However, the coefficient estimates for the squared log of abatement is: (i) negative and significant for H/PFCs and N_2O reduction and forestry projects; (ii) positive and significant for demand-side energy-efficiency and methane avoidance projects; and (iii) not significant for any other project type (see Table A.2). Consequently, the elasticities can and do deviate from mean values over observed project scale. The results of separate one-tailed tests indicate that the estimated abatement elasticities are less than one at standard critical levels for renewable resource based, demand-side energy efficiency, fossil fuel switch, H/PFCs and N_2O reduction, and afforestation and reforestation projects (Stata, 2012). The estimated abatement elasticities for methane avoidance, supply-side energy efficiency and transportation projects are not significantly different from one (Stata, 2012).

To illustrate this point, average costs of abatement for different types of CDM projects at different levels of abatement are calculated using the coefficient estimates as reported in Table A.2. Figures 4 and 5 depict the average cost curves for different types of 10-year long projects in China, which start generating CERs in 2008 and use

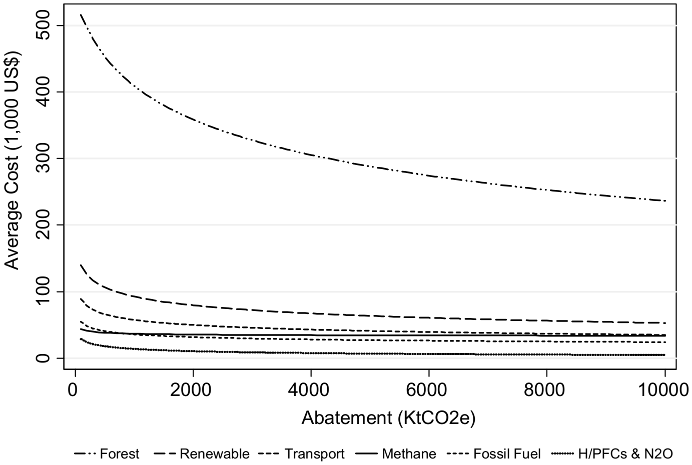

Figure 4. Estimated average abatement cost curves for forest, renewable resource-based, transport, methane avoidance, fossil fuel switch, and H/PFCs and N_2O reduction projects

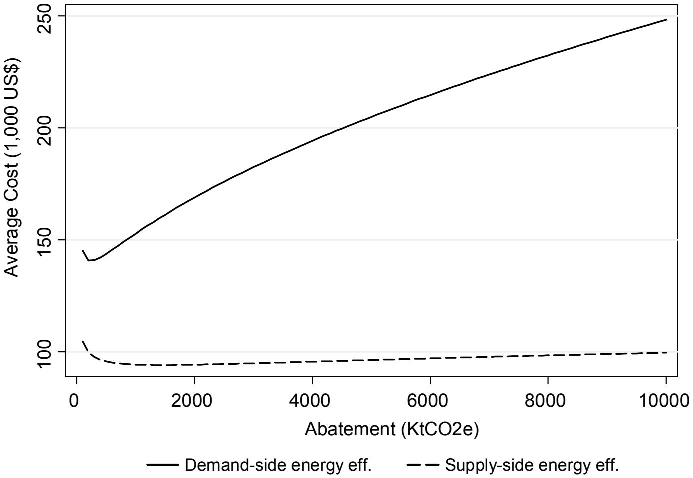

Figure 5. Estimated average abatement cost curves for demand- and supply-side energy efficiency projects

the dominant methodology for those project categories. As shown in Fig. 4, the average costs of afforestation and reforestation, renewable resource-based, transport, methane avoidance, fossil fuel switch, and H/PFCs and N_2O reduction projects continuously decrease at a decreasing rate with the volume of abatement, indicating economies of scale. However, afforestation and reforestation, renewable resource-based, and transport projects exhibit higher levels of economies of scale compared to that of methane avoidance, fossil fuel switch and H/PFCs and N_2O reduction projects. As depicted in Fig. 5, the average costs of demand- and supply-side energy efficiency projects decrease at a decreasing rate as long as the volume of abatement is less than roughly 300 and 1500 $KtCO_2e$ per year. Beyond these levels, the average costs for these classes of projects increases at a decreasing rate with the volume of abatement.

Consistent with this result, the average sizes of the renewable resource-based projects in the pipeline have increased over time and the average sizes of demand- and supply-side energy efficiency projects have remained within the range of respective economies of scale (see Fig. 6). In contrast to the result, the average sizes of H/PFCs and N_2O reduction, transportation, and fossil fuel switch projects have decreased over time, while no systematic change is observed in the sizes of methane avoidance and forest projects (see Fig. 6).

Based on the estimated average costs, mitigation by afforestation and reforestation projects appears to be most expensive, followed by abatement through demand-side energy efficiency, supply-side energy efficiency, renewable resource-based, transport, methane avoidance, and fossil fuel switch projects, respectively. Abatement by H/PFCs and N_2O reduction projects is the least costly. The distribution of the CDM projects in the pipeline does not quite follow this relative cost structure (recall Table 1).

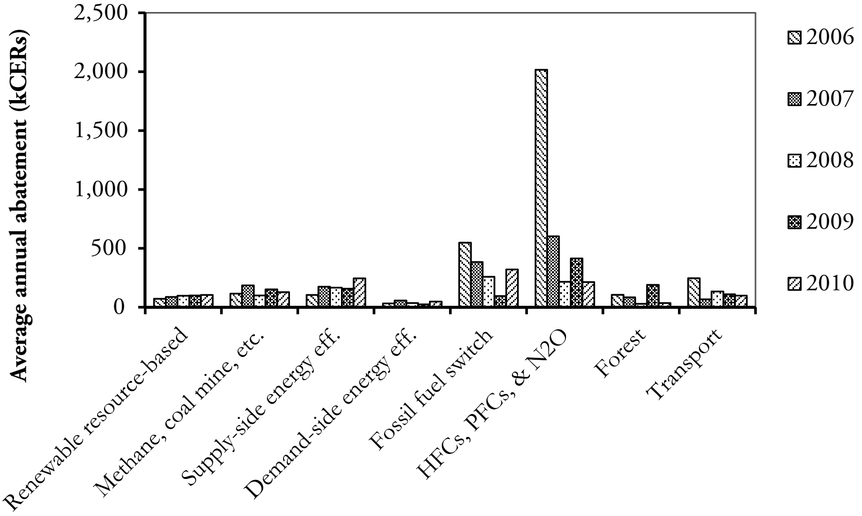

Figure 6. Average annual abatement by different types of projects during 2006–2010

Consistent with the estimated set of relative costs, the project portfolio contains few afforestation and reforestation projects; they account for less than 1% of the total CERs projects in the CDM pipeline are expected to generate. However, less than 5% of the projects in the pipeline are H/PFCs and N_2O reduction or fossil fuel switch projects, while about 77% of the projects are renewable resource-based or demand- or supply-side energy efficiency projects with much higher abatement cost.

While this finding contradicts the presumption that investors will seek out low-cost opportunities, there are several potential explanations. First, it may be the case that the lowest-cost opportunities identified in the analysis have been fully exploited and cannot be duplicated (e.g., H/PFCs and N_2O reduction projects); as a consequence, investors have moved to higher cost alternatives. Second, when risks associated with the aspects of investments and transaction are substantial relative to unit costs of generating the credits, investors and/or buyers of CERs, and by-products hold preferences about the underlying technologies used to generate offsets. Third, considering the uncertainties about the functioning of the carbon market, investors may find it less risky to invest in projects that generate tradable by-products (e.g., electricity) although projects that generate CERs only have substantially lower abatement cost.

From the estimates reported in Table 5, the duration of the project affect abatement costs of the renewable resource-based and fossil fuel switch projects only, where costs rise (fall) as the duration of the renewable (fossil fuel) projects lengthens. Note that more than 62% of the projects in the pipeline are renewable resource based while less than 3% of the projects are fossil fuel switching. The duration effect is not significantly different from zero for other project types. From this result, the duration effect appears to be an artifact of the project type.

Table 6. Results for China, India, and Brazil — elasticities and discrete-change effects.

	China	India	Brazil
Elasticities			
Abatement (KtCO$_2$e)	0.843***	0.87***	0.758***
Project duration (years)	−0.685***	0.533***	0.313
Discrete-change effects			
Project-type			
Renewable resource	7.840***	4.451***	6.475***
HFCs, PFCs, and N$_2$O	4.212***	1.580**	2.480**
Methane avoidance	6.847***	3.061***	5.526***
Supply side energy efficiency	7.233***	3.473***	5.664***
Demand side energy efficiency	7.406***	3.961***	8.435***
Fossil fuel switch	6.302***	2.713***	4.357***
Transportation	6.544***	6.106***	—
Forest	9.108***	4.977***	8.236***
Dominant methodology			
Large scale consolidated: ACM 1 (dropped)			
Large scale consolidated: ACM 2	−0.513**	−0.394*	−0.681*
Large scale consolidated: ACM 12	0.114	−0.197	0.569
Large scale: AM 34	1.590***	−0.48	—
Small scale: AMS-II.D.	0.26	−0.112	−1.760***
Small scale: AMS-III.B.	0.66	0.048	1.262***
Small scale: AMS-III.C.	—	−1.710***	—
Small scale: AMS-III.D.	−0.282***	−0.292	−0.02
AR small scale: AR-AMS 1	−0.329	−0.866***	—
Credit start-			
Prior to 2005 (dropped)			
2005	−0.22	−0.018	0.203
2006	−0.304	0.042	0.377
2007	−0.625***	−0.108	0.361
2008	−0.873***	−0.146	0.03
2009	−0.823***	−0.146	0.339*
2010	−0.575**	−0.045	0.445**
2011	−0.448**	−0.027	0.575***
2012	−1.056***	−1.225***	1.566***
Post 2012	−1.684***	−1.987***	2.679***
Methodology fixed effects	Yes	Yes	Yes
Observations	2,583	1,726	389
Adj. R-squared	0.994	0.993	0.991

Note: Only the dominant (most frequently used) methodology fixed effects are reported while the rest are suppressed to conserve space. Underlying parameter estimates are given in Table A.3. Asterisks ***, **, and * indicate significance at 1%, 5%, and 10% levels. Highlighted estimates for methodology dummies indicate the dominant methodology for each project type. The results of separate one-tailed tests indicate that the estimated abatement elasticities are less than 1.00 at 1% significance level for China, India, and Brazil.

Abatement costs in selected host countries

More than 72% of the CDM projects are located in three CDM host countries: China, India, and Brazil. In order to further examine the effects of location on abatement costs we estimate the log–quadratic model IV for the projects located in these countries separately. The elasticity and semi-elasticity estimates are presented in Table 6, and the coefficient estimates with standard errors are reported in Table A.3.[19]

Based on the estimates as reported in Table 6, cost appears to be inelastic to the volume of abatement for each of the selected countries implying economies of scale.[20] All things equal, average cost of abatement decreases (increases) with duration of the projects in China (India). Duration does not have a significant effect on the abatement cost of the projects in Brazil. Thus, the duration effect is location-specific as well. Different types of projects in the major host countries have varying levels of fixed costs. A downward trend in abatement costs is apparent for the flow of projects in China and India, while an upward trend beyond 2012 is obvious for the projects in Brazil.

Relative attractiveness of different types of projects within each individual host country differ slightly. Afforestation and reforestation, demand-side energy efficiency, and renewable resource-based projects appear to be the most expensive in all three largest CDM host countries, where H/PFCs and N_2O reduction and fossil fuel switch projects are the least expensive ones. However, more than 67%of the CDM projects in these countries are renewable resource based, while only 4% are H/PFCs and N_2O reduction and fossil fuel switch projects. Thus, the distribution of different types of projects within each of the major host countries is not skewed toward low-cost projects.

Comparing relative average costs of abatement for different types of projects in China, India, and Brazil, it appears that Brazil has a comparative advantage in H/PFCs and N_2O reduction projects, China has comparative advantages in methane avoidance, demand-side energy efficiency, and transportation projects, and India has comparative advantages in renewable resource-based, supply-side energy efficiency, fossil fuel switch, and forestry projects. Between the two largest host countries, China has comparative advantages in methane avoidance, demand-side energy efficiency, and transportation projects, while India has comparative advantages in all other types of projects. The distribution of different types of projects across these countries, however, does not quite follow the principle of comparative advantage. Most of the projects in China are renewable resource-based electricity generation projects (71%), followed by supply-side energy efficiency (15%) and methane avoidance projects (10%). Renewable resource-based projects account for 65% of the CDM projects in India, followed by demand-side (12%) and supply-side (11%) energy efficiency and methane avoidance projects (6%). In Brazil, only 2% of the projects are H/PFCs and N_2O

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[19] Due to space limitation, only the discrete-change effects for the dominant methodology in each project category (indicated by highlighted estimates) are presented in the tables.

[20] The results of one-tailed nonlinear tests indicate that the estimated elasticity for abatement is less than one at 1% significance level for the projects in China, India, and Brazil (Stata, 2012).

reduction projects while renewable resource-based projects account for 59% and methane avoidance projects account for 28%.

One potential explanation for this finding is that investors selected project types and locations based on competitive advantage rather than comparative advantage. Endowment of natural resources and national policies of the host countries attribute to competitive advantage to certain types of CDM projects. For example, the Chinese government's support for renewable energy projects includes reduced corporate income taxes, significant reductions in value added taxes, feed-in tariffs and subsidies to operators of renewable energy projects to compensate for their costs (KPMG International Cooperative, 2011). In Brazil, feed-in tariffs are available for electricity generation from wind, biomass, and hydro projects, and a special tax regime is applicable to the producers of biodiesel (KPMG International Cooperative, 2011). Because such incentives or subsidies incur social costs, renewable energy projects are even less attractive from a social standpoint. However, net social benefit from strengthening the renewable energy sector may be positive in the long run.

5. Conclusions and Policy Implications

This paper examines the costs of emissions reduction under the CDM of the Kyoto Protocol using project data. Many of the projects simultaneously generate CERs and additional by-products such as electricity, so we consider a separable cost function based on an explicit disentanglement of costs and revenue. We control for the duration of the projects, types of the projects, types of technology used in the projects, years in which the projects began, and locations of the projects. In our preferred (full) model, we employ a complete set of fixed effects associated for each host country and for each technology type, but we also estimate versions of the model employing fixed effects for broader classifications of projects and regions rather than for each technology type and host country. We repeat the analysis for specific types of projects, and also for the countries that host a large number of CDM projects. We consider log–log and log–quadratic functional forms for the cost function. From a technical perspective, we found that introducing additional flexibility in the form of a quadratic term for abatement had little effect on the estimation results.

In general, we find evidence of economies of scale at the aggregate level. At mean levels, all calculated abatement elasticities are less than one. We also find significant variation in scale effects by type of projects; for example, H/PFCs and N_2O reduction projects and renewable energy projects exhibit smaller abatement elasticities than aggregate averages, while the estimated abatement elasticities for methane avoidance, supply-side energy efficiency and transportation projects are larger than aggregate averages and not significantly different from one. Moreover, results from the flexible-form models suggest variation in scale effects over reasonable ranges for some types of projects, including demand- and supply-side energy efficiency projects. The policy implication of this result is that small CDM projects should not be promoted, unless the projects deliver other benefits in addition to mitigation benefits.

At the aggregate level, we find strong evidence that the average cost of abatement increases with project duration, even though differences in the expected timing of delivered outputs have been accounted for by discounting. However, this result is not consistent for specific project type and location. Costs increased with project duration for renewable resource-based projects and declined for fossil-fuel-switching projects. For all other types of projects, the effects of project duration on abatement cost are not significant. Similarly, we find that costs increased with project duration for the projects in India, but declined with project duration for the projects in China. Thus, the duration effect appears to be and artifact of project type and/or location.

Under the CDM rules, credits were granted for some projects that began prior to 2005. We find evidence that costs fell for post-2005 projects as CDM rules and procedures were developed. At the other end of our sample, some projects already underway are expected to produce credits beyond the first accounting period recognized under the Kyoto Protocol, and there is still uncertainty about the value of these future credits. Evidence from the full set of models is mixed for post-2012. In general, generating post-2012 credits was not associated with increased costs, rather generating post-2012 credits was either associated with lower costs, or had no distinguishable effect on cost. Despite the notion that investors would first target ‘low-hanging fruit’ before moving up the abatement cost structure, we find no evidence of an upward trend in the costs of abatement under the CDM.

We found significant variation in the costs of abatement by type and location of the projects. Surprisingly, we found little evidence that per unit costs of generating CERs were lower in the places where investments most often took place. Similarly, the types of projects that attracted larger number of investors, or larger amount of investments, were not the projects associated with lower per unit production costs. Even for the three individual host countries that we examined, investments were not concentrated in projects with the lowest per unit costs. The finding is significant, given the important role estimates of unit costs of abatement in the bottom-up and top-down models to evaluate abatement potential and analyze policy alternatives, where the presumption is that project investors will seek out low-cost opportunities.

Still, there are several potential explanations that are consistent with a market where unit costs are crucial in characterizing investment decisions. It may be the case that the lowest-cost opportunities identified in the analysis have been fully exploited and cannot be duplicated, although there is no general evidence that abatement costs are rising. Alternatively, it may be the case that investors selected project types and locations based on competitive advantage rather than comparative advantage where national policies of the host countries confer competitive advantage to certain types of CDM projects. In addition, future research may find contrasting evidence by improving our underlying cost models and using data with more details. However, it is worth pointing out that unit production costs do not necessarily reflect the true cost or value to investors. In this regard, our findings are consistent with the notion that various costs associated with transactions are significant relative to unit costs and the possibility that eventual buyers of CERs hold preferences about the underlying technologies used to generate offsets, which in turn creates incentives for investors to differentiate the value of projects by type. We think that this is a potentially important topic for future research, as our analysis intentionally avoided ascribing costs or benefits that might arise outside of what is considered by the CDM Board.

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Appendix A

Table A.1. Estimation results of the log–log and log–quadratic models.

	Log–log: I	Log–quad.: II	Log–quad.: III	Log–quad.: IV
Log of abatement ($KtCO_2e$)	0.900***	0.674***	0.580***	0.776***
	(0.044)	(0.212)	(0.062)	(0.067)
Squared log of abatement	—	0.019	0.019***	0.007
	—	(0.021)	(0.005)	(0.006)
Log of project duration (years)	0.952**	0.950**	1.087***	0.363*
	(0.482)	(0.473)	(0.080)	(0.133)
Project-type dummies				
Renewable resource	4.032***	4.645***	5.084***	4.957***
	(1.331)	(0.994)	(0.267)	(0.054)
HFCs, PFCs, and N_2O	1.722	2.244**	2.610***	2.318***
	(1.251)	(0.966)	(0.282)	(0.095)
Methane avoidance	3.149**	3.759***	4.214***	3.927***
	(1.223)	(0.894)	(0.267)	(0.057)
Supply side energy efficiency	3.537***	4.148***	4.486***	4.128***
	(1.270)	(0.945)	(0.279)	(0.079)
Dem. side energy efficiency	4.064***	4.661***	5.145***	4.488***
	(1.226)	(0.914)	(0.269)	(0.087)
Fossil fuel switch	3.177**	3.750***	4.215***	3.598***
	(1.247)	(0.952)	(0.270)	(0.199)
Transportation	4.720***	5.336***	5.747***	3.850***
	(1.234)	(0.924)	(0.289)	(0.137)
Forest	3.972**	4.570***	6.046***	6.395***
	(1.682)	(1.327)	(0.351)	(0.126)
Methodology dummies				
Large scale consolidated: ACM (dropped)				
Large scale: AM			0.093*	
			(0.050)	
Small scale: AMS			−0.421***	
			(0.037)	

Table A.1. (*Continued*)

	Log–log: I	Log–quad.: II	Log–quad.: III	Log–quad.: IV
AR large scale cons.: AR-ACM			−1.344***	
			(0.279)	
AR large scale: AR-AM			−1.063***	
			(0.279)	
AR small scale: AR-AMS			−1.730***	
			(0.277)	
Credit start-year dummies				
Prior to 2005 (dropped)				
2005	−0.455	−0.447	−0.419**	−0.132
	(0.372)	(0.366)	(0.184)	(0.095)
2006	−0.337	−0.337	−0.282***	−0.039
	(0.233)	(0.229)	(0.108)	(0.031)
2007	−0.120***	−0.113**	−0.044	−0.001
	(0.044)	(0.048)	(0.068)	(0.107)
2008	−0.293***	−0.279**	−0.210***	−0.133
	(0.112)	(0.113)	(0.066)	(0.099)
2009	−0.288***	−0.272***	−0.202***	−0.066
	(0.066)	(0.069)	(0.064)	(0.131)
2010	−0.14	−0.128	−0.06	0.102
	(0.086)	(0.081)	(0.063)	(0.113)
2011	−0.058	−0.046	−0.011	0.178
	(0.062)	(0.060)	(0.067)	(0.105)
2012	−0.381**	−0.371**	−0.344***	−0.139
	(0.167)	(0.178)	(0.123)	(0.359)
Post 2012	−0.528*	−0.593**	−0.477	−0.277
	(0.317)	(0.257)	(0.307)	(0.661)
Regional dummies				
Africa (dropped)				
Asia and Pacific	−0.247***	−0.241***	−0.248***	
	(0.062)	(0.061)	(0.070)	
Europe and central Asia	−0.395**	−0.402**	−0.454***	
	(0.174)	(0.175)	(0.123)	
Latin America	−0.135	−0.139	−0.211***	
	(0.124)	(0.123)	(0.079)	
Middle East	−0.014	0.011	−0.054	
	(0.113)	(0.113)	(0.110)	
Observations	6,326	6,326	6,326	6,326
Adjusted R-squared	0.991	0.991	0.991	0.993

Note: Asterisks ***, **, and * indicate significance at 1%, 5%, and 10% levels. Estimates of methodology dummies and host country dummies for model IV are suppressed due to space limitation.

Table A.2. Estimation results for different types of CDM projects.

	Renewable	HFCs	Methane	SS-EE	DS-EE	FFS	Transport	Forest
Log of abatement	0.98***	1.07***	0.83***	0.78*	0.55***	0.78***	0.88	1.25***
	(0.09)	(0.23)	(0.07)	(0.29)	(0.07)	(0.15)	(0.95)	(0.14)
Squared log of abatement	−0.01	−0.03**	0.01*	0.02	0.04***	0.01	−0.01	−0.03**
	(0.01)	(0.01)	(0.00)	(0.02)	(0.01)	(0.01)	(0.09)	(0.01)
Log of project duration	0.26***	−0.98	−0.03	0.05	−0.11	−0.41*	−0.50	−0.08
	(0.03)	(1.47)	(0.16)	(0.04)	(0.07)	(0.15)	(0.22)	(0.21)
Dominant methodology dummies								
Large scale con.: ACM 1 (dropped)								
Large scale con.: ACM 2	0.07**	—	—	5.78***	—	—	—	—
	(0.02)	—	—	(0.95)	—	—	—	—
Large scale con.: ACM 12	1.84***	—	—	5.34***	5.91***	—	—	—
	(0.05)	—	—	(1.00)	(0.06)	—	—	—
Large scale: AM 34	—	—	—	6.53***	—	−0.87***	—	—
	—	—	—	(0.95)	—	(0.10)	—	—
Small scale: AMS-II.D.	—	—	—	—	—	—	0.91*	—
	—	—	—	—	—	—	(0.08)	—
Small scale: AMS-III.B.	—	1.99***	—	—	—	—	—	—
	—	(0.41)	—	—	—	—	—	—
Small scale: AMS-III.C.	−0.82***	—	−1.34***	—	5.68***	—	—	—
	(0.01)	—	(0.04)	—	(0.14)	—	—	—
Small scale: AMS-III.D.	1.09***	—	0.011	5.55***	6.24***	0.07	—	—
	(0.03)	—	(0.07)	(0.93)	(0.05)	(0.16)	—	—
AR small: AR-AMS1	0.99	—	—	—	6.25***	−0.30	—	—
	(0.61)	—	—	—	(0.07)	(0.22)	—	—

Table A.2. (*Continued*)

	Renewable	HFCs	Methane	SS-EE	DS-EE	FFS	Transport	Forest
Credit start-year dummies								
Prior to 2005 (dropped)								
2005	−0.14	−0.07	−0.65*	0.14	0.22***	−0.44	—	—
	(0.07)	(0.43)	(0.24)	(0.07)	(0.01)	(0.30)	—	—
2006	0.08***	−0.55	−0.24	0.04	−0.05*	0.14	0.13	−0.32*
	(0.01)	(0.64)	(0.18)	(0.07)	(0.02)	(0.26)	(0.39)	(0.13)
2007	−0.05	−0.33*	−0.12	−0.16*	−0.02*	0.05	−0.09	−0.33
	(0.15)	(0.14)	(0.17)	(0.06)	(0.01)	(0.27)	(0.17)	(0.37)
2008	−0.28	−0.01	−0.13	−0.16	−0.07***	−0.09	−0.15	−0.17
	(0.14)	(0.29)	(0.23)	(0.11)	(0.01)	(0.29)	(0.29)	(0.16)
2009	−0.15	−0.28	−0.13	−0.13	−0.05***	−0.52	0.2	−0.19
	(0.16)	(0.22)	(0.14)	(0.09)	(0.01)	(0.54)	(0.21)	(0.23)
2010	0.06	0.54	−0.12	−0.12**	−0.05***	−0.25	0.17	−0.03
	(0.14)	(0.40)	(0.17)	(0.04)	(0.00)	(0.40)	(0.14)	(0.40)
2011	0.18	0.24	−0.07	− 0.14	0.04	0.03	−0.12	1.11***
	(0.12)	(0.59)	(0.12)	(0.10)	(0.02)	(0.29)	(0.28)	(0.14)
2012	−0.39	2.97*	0.12	−0.17*	0.40	—	—	—
	(0.46)	(1.16)	(0.15)	(0.07)	(0.22)	—	—	—
Post 2012	−0.24	—	−0.15	−2.45***	—	—	7.72	—
	(1.02)	—	(0.08)	(0.09)	—	—	(2.00)	—
Selected host country dummies								
Albania (dropped)								
Brazil	5.34***	3.94	5.64***	0.76***	1.09***	6.96***	—	−0.17
	(0.04)	(4.26)	(0.14)	(0.05)	(0.08)	(1.06)	—	(0.21)
China	4.93***	4.03	5.19***	0.05**	0.26***	6.85***	6.61	0.20
	(0.09)	(4.09)	(0.11)	(0.02)	(0.03)	(1.38)	(1.95)	(0.37)

Table A.2. (*Continued*)

	Renewable	HFCs	Methane	SS-EE	DS-EE	FFS	Transport	Forest
India	5.78***	3.67	5.21***	0.02	0.58***	6.61***	7.83	0.15
	(0.05)	(4.56)	(0.10)	(0.04)	(0.05)	(1.23)	(1.82)	(0.40)
Mexico	5.69***	3.15	4.51***	0.35***	0.46***	—	6.79	—
	(0.05)	(3.96)	(0.14)	(0.06)	(0.03)	—	(2.42)	—
Malaysia	5.33***	—	5.05***	−0.35	0.27***	—	—	—
	(0.12)	—	(0.11)	(0.49)	(0.04)	—	—	—
Observations	3,919	116	1,129	636	301	120	35	68
Adj. R-squared	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

Note: Asterisks ***, **, and * indicate significance at 1%, 5%, and 10% levels.

Table A.3. Estimation results for selected CDM host countries: Brazil, China, and India.

	China	India	Brazil
Log of abatement ($KtCO_2e$)	1.013***	1.266***	0.489
	(0.207)	(0.168)	(0.353)
Squared log of abatement	−0.013	−0.038**	0.029
	(0.015)	(0.017)	(0.032)
Log of project duration (years)	−0.685***	0.533***	0.313
	(0.160)	(0.195)	(0.273)
Project-type dummies			
Renewable resource	7.840***	4.451***	6.475***
	(0.829)	(0.645)	(0.999)
HFCs, PFCs, and N_2O	4.212***	1.580**	2.480**
	(0.655)	(0.672)	(1.007)
Methane avoidance	6.847***	3.061***	5.526***
	(0.788)	(0.613)	(0.982)
Supply side energy efficiency	7.233***	3.473***	5.664***
	(0.805)	(0.630)	(1.029)
Demand side energy efficiency	7.406***	3.961***	8.435***
	(0.796)	(0.619)	(1.001)
Fossil fuel switch	6.302***	2.713***	4.357***
	(0.930)	(0.677)	(0.986)
Transportation	6.544***	6.106***	—
	(0.842)	(0.580)	—
Forest	9.108***	4.977***	8.236***
	(0.881)	(0.695)	(1.238)
Methodology dummies			
Large scale consolidated: ACM 1 (dropped)			
Large scale consolidated: ACM 2	−0.513**	−0.394*	−0.681*
	(0.243)	(0.235)	(0.371)
Large scale consolidated: ACM 12	0.114	−0.197	0.569
	(0.303)	(0.241)	(0.408)
Large scale: AM 34	−0.081	1.164	—
	(0.524)	(0.801)	—
Small scale: AMS-II.D.	1.375***	—	—
	(0.419)	—	—
Small scale: AMS-III.B.	1.590***	−0.48	—
	(0.270)	(0.464)	—
Small scale: AMS-III.C.	−1.747***	−0.565**	−1.777***
	(0.248)	(0.238)	(0.469)
Small scale: AMS-III.D.	0.26	−0.112	−1.760***
	(0.353)	(0.230)	(0.517)
AR small scale: AR-AMS 1	0.66	0.048	1.262***
	(0.535)	(0.338)	(0.414)
Credit start-year dummies			
Prior to 2005 (dropped)			
2005	−0.220	−0.018	0.203

Table A.3. (*Continued*)

	China	India	Brazil
	(0.320)	(0.148)	(0.178)
2006	−0.304	0.042	0.377
	(0.265)	(0.105)	(0.239)
2007	−0.625***	−0.108	0.361
	(0.233)	(0.091)	(0.230)
2008	−0.873***	−0.146	0.03
	(0.225)	(0.090)	(0.248)
2009	−0.823***	−0.146	0.339*
	(0.223)	(0.095)	(0.187)
2010	−0.575**	−0.045	0.445**
	(0.223)	(0.087)	(0.205)
2011	−0.448**	−0.027	0.575***
	(0.225)	(0.095)	(0.214)
2012	−1.056***	−1.225***	1.566***
	(0.262)	(0.318)	(0.375)
Post 2012	−1.684***	−1.987***	2.679***
	(0.225)	(0.392)	(0.354)
Observations	2,583	1,726	389
Adj. R-squared	0.995	0.993	0.993

Note: Asterisks ***, **, and * indicate significance at 1%, 5%, and 10% levels.

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