

# An alternative way to mitigate non-additionality risks of carbon offsets

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## Article

**Keywords:** carbon offsetting, carbon markets, additionality, positive lists, regime design

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# **An alternative way to mitigate non-additionality risks of carbon offsets\***

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## **Abstract**

The market for carbon credits is riddled with problems. Despite lengthy and costly case-by-case approval processes, often too many credits are awarded per project (over-crediting), and many projects would have happened anyway (non-additionality). Here we investigate a novel additionality regime based on: (i) dynamic positive lists that define automatic eligibility criteria, specified by host country and by project type; and (ii) partial credit issuance to reflect context-specific non-additionality risks. We carry out simulation analysis, conducted on a synthetic project pool calibrated on historical data, to demonstrate that this approach performs better than current practice under most scenarios in terms of emissions reductions, cost efficiency, and resilience against systematic over-crediting. The findings support a standardised assessment approach over project-specific evaluation, and they call for more disaggregated analysis across heterogeneous contexts to mitigate regulatory biases and deliver a simpler certification process with better climate outcomes.

**Keywords:** carbon offsetting, carbon markets, additionality, positive lists, regime design

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## 1. Main

In theory, a well-functioning carbon market offers important benefits. First, it improves the economics of clean projects that contribute to additional emissions reduction or carbon removal<sup>1,2</sup>. Second, it helps minimise overall abatement costs and increase economic efficiency<sup>3</sup>, compared to conventional regulation. Third, it provides a source of climate finance for sustainable development initiatives in developing countries<sup>4,5</sup> and contributes to climate justice<sup>6</sup>. Fourth, it establishes a pathway for individuals, corporations, and governments to voluntarily claim climate contributions or fulfil climate pledges<sup>7,8</sup>. Finally, it functions as a political tool to encourage international cooperation and collective climate action<sup>9,10</sup>.

In practice, carbon markets have fallen short of these objectives. The credits used to offset carbon emissions must be ‘real, additional, quantifiable, permanent<sup>11</sup>, verifiable, and enforceable’<sup>12</sup>. Attaining this level of integrity has proven difficult.

Additionality is the most challenging requirement<sup>12,13</sup> due to inherent information asymmetries<sup>14–17</sup>. Developers need to convince potential investors that the project is low-risk and capable of generating stable returns, while simultaneously persuading regulators that the project is not financially viable without credit revenues<sup>13,18</sup>. Faced with this dilemma, they have an incentive to inflate the project’s internal rate of return (IRR) when presenting it to investors and deflate it to exaggerate additionality when reporting to regulators. With imperfectly disclosed information and large variations in country contexts and project types<sup>16</sup>, regulators face a statistical probability of rejecting genuinely additional projects (“false negatives”) and approving non-additional projects (“false positives”)<sup>17</sup>. Non-additional credits trading at lower prices can then distort the carbon market<sup>12,17</sup>, creating a false illusion of decarbonisation progress<sup>12</sup>.

Existing certification regimes have responded to the challenge with an increasingly complex and costly approval process, which subjects projects to a variety of additionality tests (see Supplementary Figure 2)<sup>19</sup>. A large body of literature has reported that despite these tests, many credits are not additional, that is, the project outcomes would have been achieved anyway<sup>14,19–24</sup>. More recent initiatives prioritise standardised approaches that set pre-determined project type-specific eligibility criteria<sup>25</sup>, emphasize oversight by host countries<sup>26</sup>, and set higher restrictions to ensure not only financial additionality but also regulatory or target additionality (i.e. activities not mandated by law or going beyond NDC targets)<sup>26</sup>. This can add further complexity to the current regime, lead to fragmented governance systems, and create an overwhelming administrative burden.

35 Learning from this experience and the extant literature<sup>27,28</sup>, this paper proposes an  
36 alternative credit allocation rule that treats additionality as a continuous rather than a binary  
37 measure. There is a statistical probability that an individual project is non-additional, which  
38 depends on project type and host country context. We propose a novel regime of context-  
39 specific positive lists of projects that are eligible a priori, but the credits awarded to them are  
40 reduced to reflect the statistical risk of non-additionality. The positive lists are dynamic to  
41 accommodate context changes, for example, the introduction of a new climate target or new  
42 support policies. The estimation of non-additionality risks relies on the disaggregation and  
43 contextual analysis of historical data and industry/market experience, while the timely update  
44 of positive lists and baseline crediting rates account for context changes.

45 We use simulation analysis to compare the performance of this proposed approach to  
46 traditional case-by-case additionality assessments. Projects are drawn randomly from a  
47 synthetic pool of potential carbon offset projects, calibrated on historical data, and processed  
48 through the two approaches. Since the true project characteristics of the synthetic pool are  
49 known, we can assess the ability of the two approaches to deal with non-additional projects.

50 In our main scenario, we adopt conservative but realistic assumptions about the  
51 proportion of additional projects, benchmark IRRs, regulatory accuracy and unbiasedness,  
52 and crediting rates, based on historical data from the Clean Development Mechanism (CDM)  
53 Pipeline. The simulation outcome shows that the proposed regime results in smaller credit  
54 trade volumes, higher real carbon emission reductions, and a higher emission reduction  
55 efficiency, compared to the current regime.

56 The relative performance of the new approach depends on regulatory quality under the  
57 current regime. Keeping the characteristics of the synthetic project pool unchanged, we  
58 conduct sensitivity analysis with respect to regulation unbiasedness ( $R_p$ ), accuracy ( $k$ ), and  
59 baseline crediting rate ( $b$ ) (see Supplementary Table 1). The result shows that our proposed  
60 regime also outperforms current practice under most regulatory scenarios unless the current  
61 regulation is unbiased and accurate.

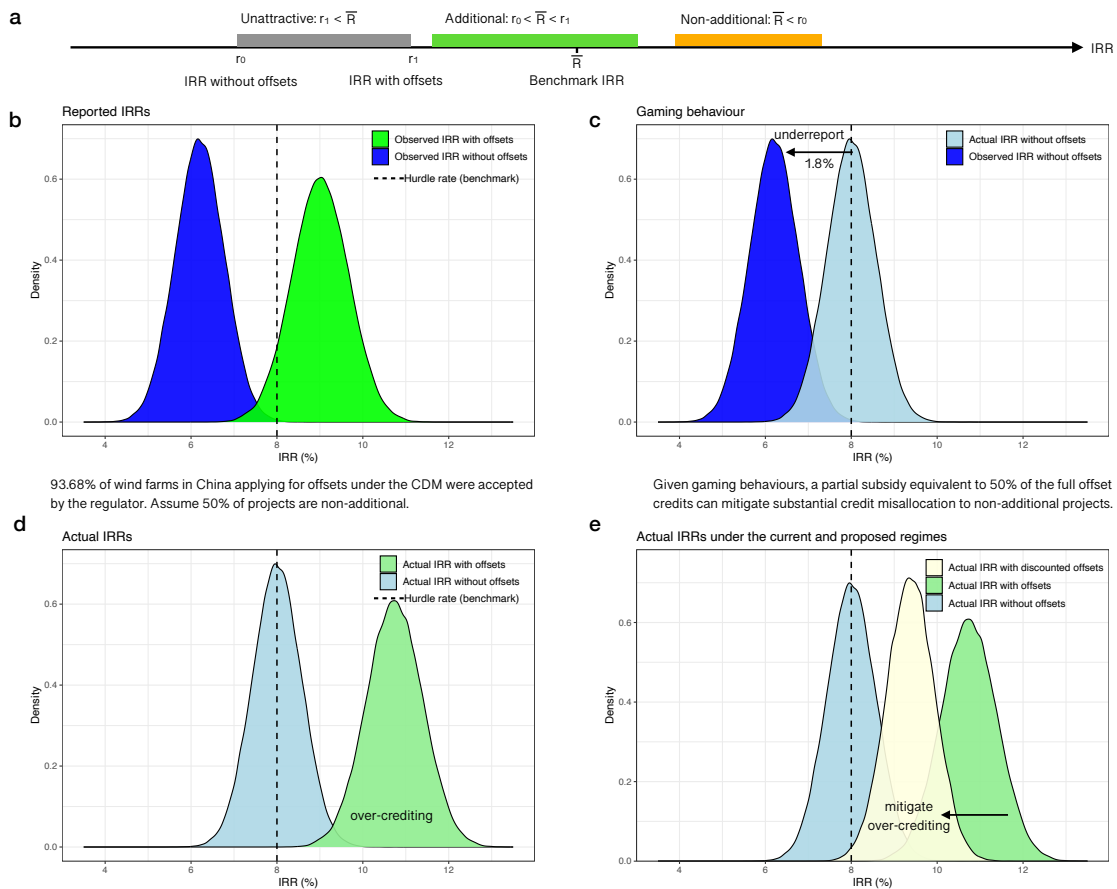
62 To simulate systematic over-crediting, we introduce an exogenous variable to measure  
63 the fraction of over-credited offsets and find that the proposed regime demonstrates greater  
64 flexibility and resilience in addressing the challenges posed by systematic over-crediting.

65 We also use sensitivity analysis to examine the performances of the two regimes under  
66 different synthetic project pools, with different proportions of additional projects and various  
67 extents of context heterogeneity, while keeping regulation quality constant. The results  
68 suggest that our proposed regime requires reasonable categorisation of contexts and careful  
69 disaggregated industry analysis to reduce uncertainties and set baseline crediting rates.

70 **2. Introducing continuous additionality to reduce bias**

71 We use CDM data from wind projects in China to construct the synthetic project pool for our  
 72 simulation analysis. Chinese wind projects were chosen for three reasons. First, the sample  
 73 size is comparatively large ( $n = 1614$ ). Second, the context is relatively homogeneous as all  
 74 projects involve a single technology, the construction of wind farms. Third, the CDM pipeline  
 75 offers detailed statistical data on project characteristics and financial metrics, which the  
 76 voluntary carbon market (VCM) does not.

77



78

79 **Figure 1. Illustration of gaming behaviour and partial credit allocation benefits**

80 **a**, Categorisation of three project types (unattractive, additional, and non-additional) based on IRRs  
 81 without/with credits. **b**, Distributions of observed reported IRRs without/with credits (dark blue/green)  
 82 in comparison to the benchmark IRR (8%) in the context of wind farms in China. **c**, Distributions of  
 83 observed reported IRR without credits (dark blue) and actual unobserved IRR without credits (light  
 84 blue). **d**, Distributions of unobserved actual IRRs without/with credits (dark blue/green) in comparison  
 85 to the benchmark IRR. **e**, Distributions of actual IRR with partial credits (light yellow).

86

87 The data sheds light on the drivers behind a project's additionality. A project is deemed  
88 financially additional if the IRR without credits falls below the hurdle rate (also known as  
89 benchmark IRR) but exceeds the hurdle rate when credit revenues are included. If the IRR  
90 without credits is above the hurdle rate, the project is non-additional. If the IRR is below the  
91 hurdle rate even with credits, the project is financially unattractive and will not be pursued  
92 (Fig. 1a). It follows that the distributions of reported project IRRs without and with credits lie  
93 on opposite sides of the hurdle rate (Fig. 1b).

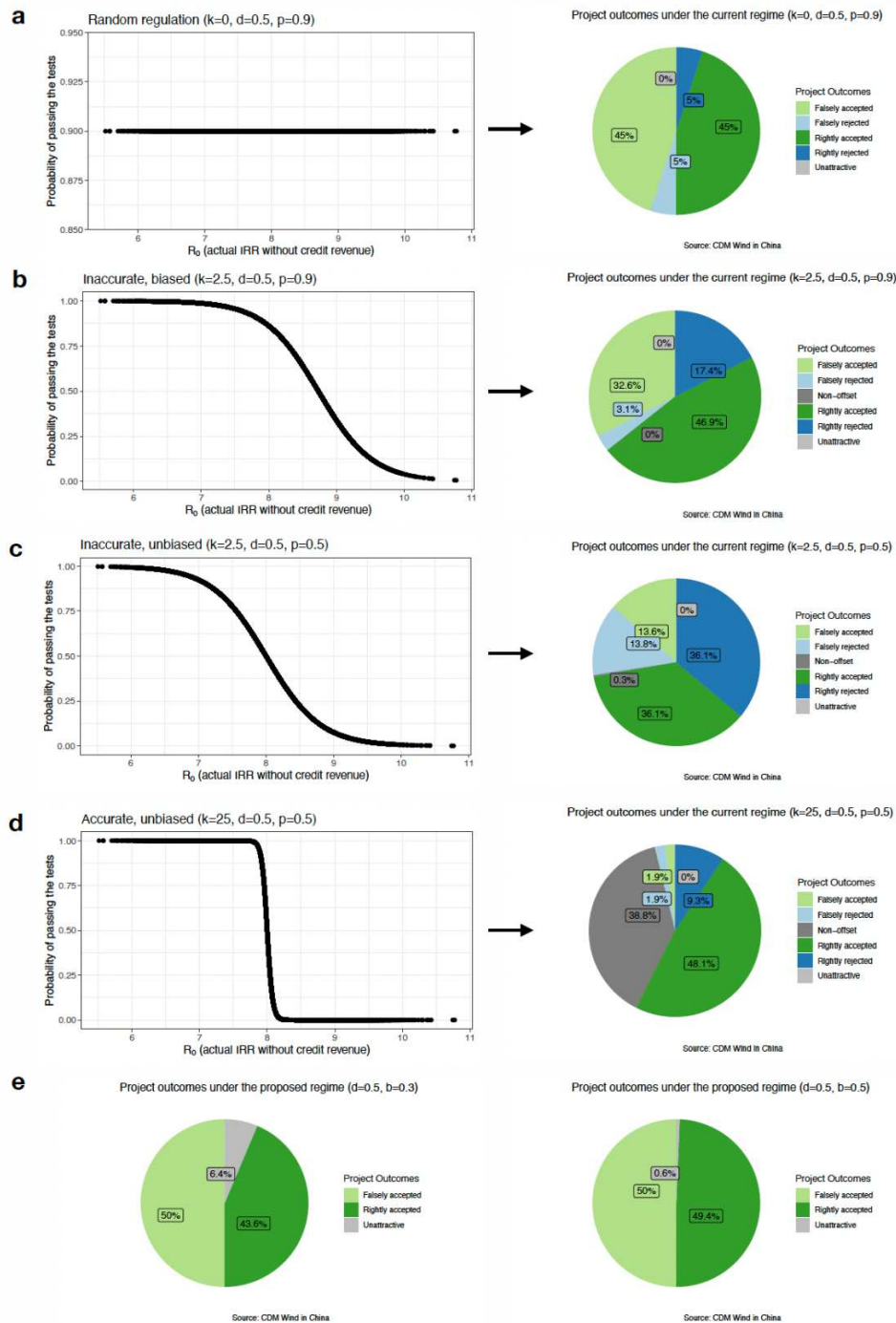
94 To pass the additionality test, project developers are likely to underreport their pre-credit  
95 IRRs (Fig. 1c), and the regulator may over-credit additional projects and accept non-  
96 additional projects as a result (Fig. 1d). For example, 65% of Indian wind farms applying for  
97 credits were accepted by the CDM, yet recent research has found that 56% of accepted  
98 projects were non-additional<sup>20</sup>.

99 Within the context of Chinese wind projects, the overall acceptance rate was 94%,  
100 suggesting a high risk of inclusion bias. Drawing on the evidence from India, we assume that  
101 the proportion of additional projects is 50% in the main scenario. The amount of credits  
102 generated by non-additional projects, accepted based on their underreported IRRs, therefore  
103 results in substantial credit misallocation (Fig. 1d). In contrast, applying a partial credit  
104 allocation rule would reduce the volume of credits issued and ensure that the IRR with credit  
105 revenues exceeds the hurdle rate for almost all projects (Fig. 1e). Compared to individual  
106 project assessments, the benefits of context-based partial credit allocation rules rooted in  
107 continuous additionality stand out.

108

### 109 **3. Comparing the two additionality regimes**

110 We first study the financial and emissions reduction outcomes of the current additionality  
111 regime and the proposed standardised regime in isolation. For the current project-based  
112 regime, we differentiate between four levels of regulatory quality: (1) random regulation  
113 where each project has the same probability of acceptance independent of the project IRR  
114 (Fig. 2a); (2) inaccurate and positively-biased regulation where the regulator may falsely  
115 reject marginally additional projects and accept marginally non-additional projects, but false  
116 acceptances are more likely (Fig. 2b); (3) inaccurate but unbiased regulation where the  
117 regulator falsely accepts and rejects offset projects in equal proportion (Fig. 2c); (4) accurate  
118 and unbiased regulation where the regulator deals with information asymmetry very well and  
119 rarely makes any false acceptances or rejections (Fig. 2d).



120

121 **Figure 2. Categories of project outcomes under the current and proposed regime**

122 **a**, Project outcomes under random regulation (each project has the same probability of acceptance  
 123 independent of its IRR). **b**, Project outcomes under inaccurate and positively biased regulation (false  
 124 acceptances are more likely than false rejections, i.e. the regime is too lenient). **c**, Project outcomes  
 125 in face of inaccurate but unbiased IRR regulation (false acceptances and false rejections are equally  
 126 likely). **d**, Project outcomes under accurate unbiased regulation (regulatory quality is near-perfect;  
 127 both false acceptances and false rejections are extremely rare). **e**, Project outcomes with crediting  
 128 rates of 0.3 and 0.5 under the proposed regime (that is, 3 or 5 credits are awarded for every 10  
 129 submitted, respectively). “Non-offset” refers to the outcome that a non-additional project does not

130 apply for credits. Higher-quality regulation is associated with a higher proportion of non-offset projects.  
131 A lower crediting rate is associated with a higher proportion of unattractive projects.

132

133 Regulatory quality is known to project developers, and it shapes their decisions. If the  
134 regulation is lenient or even random, project developers will readily apply for credits to  
135 secure the likely extra revenues (Fig. 2a, 2b). They may also submit non-additional  
136 applications under an inaccurate yet unbiased regulation (Fig. 2c). The submission of non-  
137 additional project dries up in the case of accurate and unbiased regulation (Fig. 2d), as the  
138 likelihood of being accepted is slim.

139 As credits from falsely accepted non-additional projects enter the international carbon  
140 market, they will loosen carbon constraints elsewhere, leading to overall higher emissions.

141 Under the proposed regime, the regulator does not assess individual projects and grants  
142 approval to all qualifying projects in context-based positive lists. There are no false  
143 rejections, and the likelihood of false acceptances is addressed by imposing a baseline  
144 crediting rate, which is estimated from available industry and market data. We distinguish two  
145 cases, with crediting rates of 0.3 and 0.5, respectively. That is, 3 or 5 credits are awarded for  
146 every 10 credits submitted (Fig. 2e). A potential issue with this approach is that a portion of  
147 additional projects becomes unattractive because of the reduced credit revenues. As such,  
148 setting a reasonable baseline crediting rate is essential to improve the effectiveness of the  
149 regime.

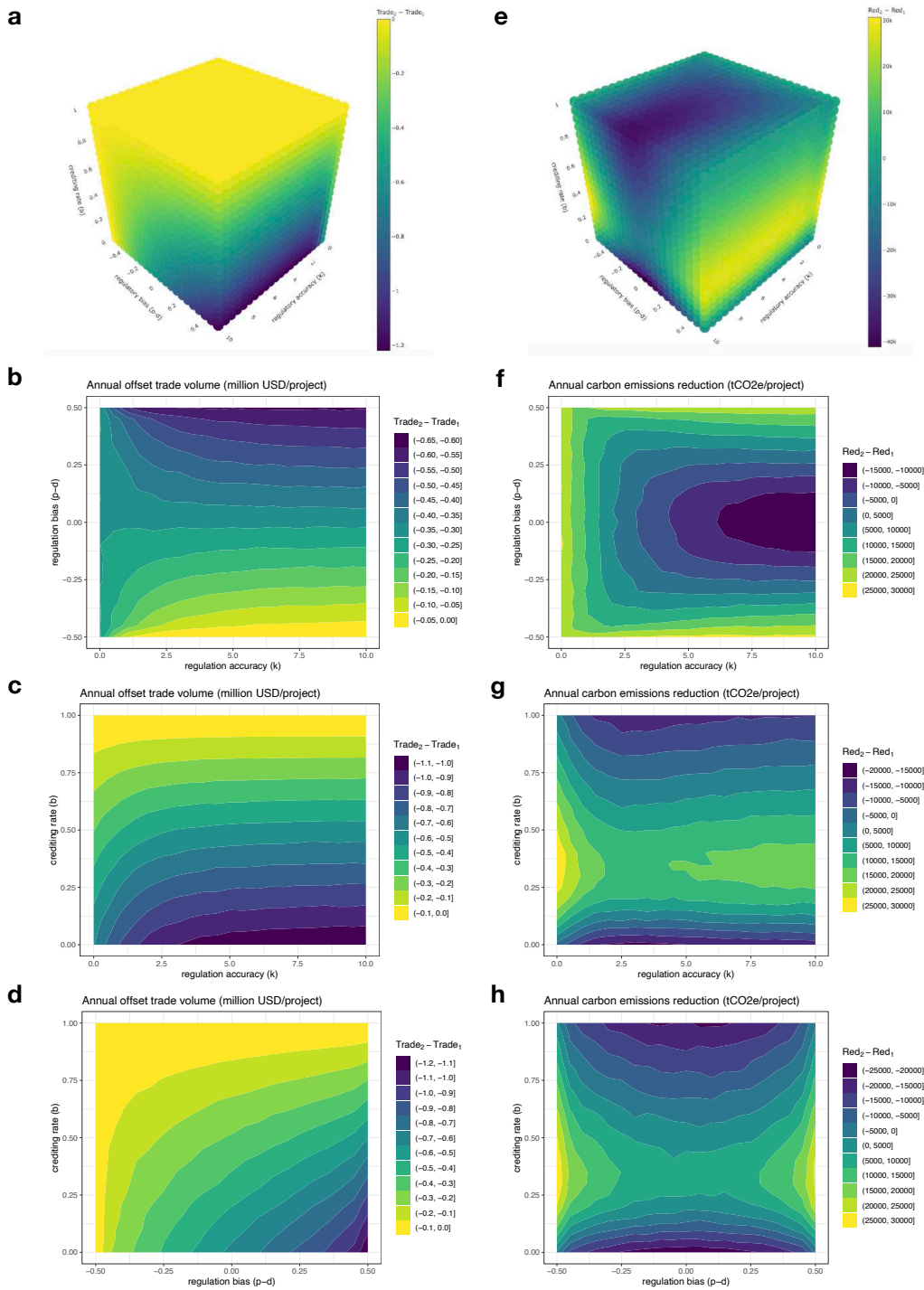
150 The most realistic case may be the scenario with inaccurate and inclusively biased  
151 regulation, given an observed registration rate of over 90% and a benchmark IRR of 8% (Fig.  
152 2b). We take this type of regulatory quality as the main scenario and assume that the  
153 additional proportion ( $d$ ) and the baseline crediting rate are both 0.5. The simulation results  
154 show that under the proposed regime: 1) the annual trade volume decreases by 485,800  
155 USD per project on average; 2) the annual carbon emission reduction on average increases  
156 by 9,959 tonnes CO<sub>2</sub>e per project; and 3) the emissions reduction efficiency improves from  
157 16,395 tCO<sub>2</sub>e/million USD to 53,290 tCO<sub>2</sub>e/million USD annually. This suggests that the  
158 proposed regime adopted in the context of Chinese wind projects outperforms the current  
159 regime environmentally, with higher real carbon emissions reductions and a higher emissions  
160 reduction efficiency, but results in lower trade volumes, that is, lower financial flows to  
161 projects.

162

#### 163 **4. Sensitivity analysis**

164 Besides the main scenario, we evaluate how project outcomes and performance metrics  
 165 change in response to varying levels of regulatory quality, project pool characteristics, and  
 166 over-crediting.

167



168

169 **Figure 3. Sensitivity analysis across different levels of regulatory quality under two**  
 170 **regimes**

171 **a**, The 3D surface plot for changes in annual trade volume per project under the proposed regime  
172 relative to the current regime, as a function of regulatory bias, accuracy, and crediting rate. **b**, Contour  
173 plot for annual trade volume (measured in million USD per project) given the crediting rate of 0.5. **c**,  
174 Contour plot for annual trade volume given the acceptance rate of 0.9. **d**, Contour plot for annual trade  
175 volume given the regulatory accuracy of 2.5. **e**, The 3D surface plot for changes in carbon emission  
176 reduction per project under the proposed regime relative to the current regime, as a function of  
177 regulatory bias, accuracy, and crediting rate. **f**, Contour plot for annual carbon emission reduction  
178 (measured in tCO<sub>2</sub>e per project) given the crediting rate of 0.5. **g**, Contour plot for annual carbon  
179 emission reduction given the acceptance rate of 0.9. **h**, Contour plot for annual carbon emission  
180 reduction given the regulatory accuracy of 2.5. Here, **b-d**, and **f-h** are cross-sections of the cubes **a**  
181 and **e** by changing two parameters and keeping one unchanged.

182

### 183 **Sensitivity analysis to regulatory quality**

184 First, we keep the synthetic project pool unchanged and change the regulation  
185 biasedness, accuracy, and crediting rate. Specifically, we set the regulator's belief in the  
186 proportion of additional projects ( $p$ ) between 0 and 1, and the regulatory bias is measured by  
187  $p - d$ . The accuracy ranges from 0 (random decision) to 10 (accurate), and the crediting rate  
188 also varies between 0 (no payment) and 1 (full payment). We compare the difference in  
189 annual credit trade volume (Fig. 3a) and carbon emission reduction (Fig. 3e) under the two  
190 regimes.

191 The results show that 1) the credit trade volume is always lower under the proposed  
192 regime (Fig. 3b); 2) a lower crediting rate is associated with a smaller credit trade volume  
193 (Fig. 3c, 3d); 3) a slightly-lower crediting rate (around 0.4, less than 0.5) under the proposed  
194 regime tends to achieve the highest increase in emission reduction (Fig. 3g, 3h); 4) the  
195 current regime outperforms the proposed one only if it is unbiased and accurate and the  
196 crediting rate in the proposed regime is far away from the true additional proportion ( $d < 0.2$   
197 or  $d > 0.6$ ) (Fig. 3f).

198

### 199 **Sensitivity analysis to over-crediting**

200 To simulate systematic over-crediting, we next introduce an exogenous variable to the  
201 main scenario, representing a fraction of over-crediting. The over-crediting of projects can  
202 also arise from overestimation of carbon emissions reduction, as a result of inaccurate  
203 baselines and methodologies during the developmental and validation stages. Here, we  
204 assume a certain share of credits are not real, i.e., they are over-issued credits, ranging  
205 between 0% (no over-issued credits) and 100% (all credits are over-issued). The average

206 annual emission reduction per project declines to zero when around 35% of credits are over-  
207 credited under the current regime, while under the proposed regime with a crediting rate of  
208 0.5, the emission reduction does not decline to zero until over 50% of credits are over-  
209 credited (Fig. 4a). In addition, when the over-crediting fraction is below 65%, the climate  
210 mitigation efficiency of the proposed regime remains higher compared to the current regime  
211 (Fig. 4b). This suggests that the proposed regime can be made more flexible and resilient  
212 toward the challenge of systematic over-crediting by applying a lower crediting rate as a  
213 safety margin.

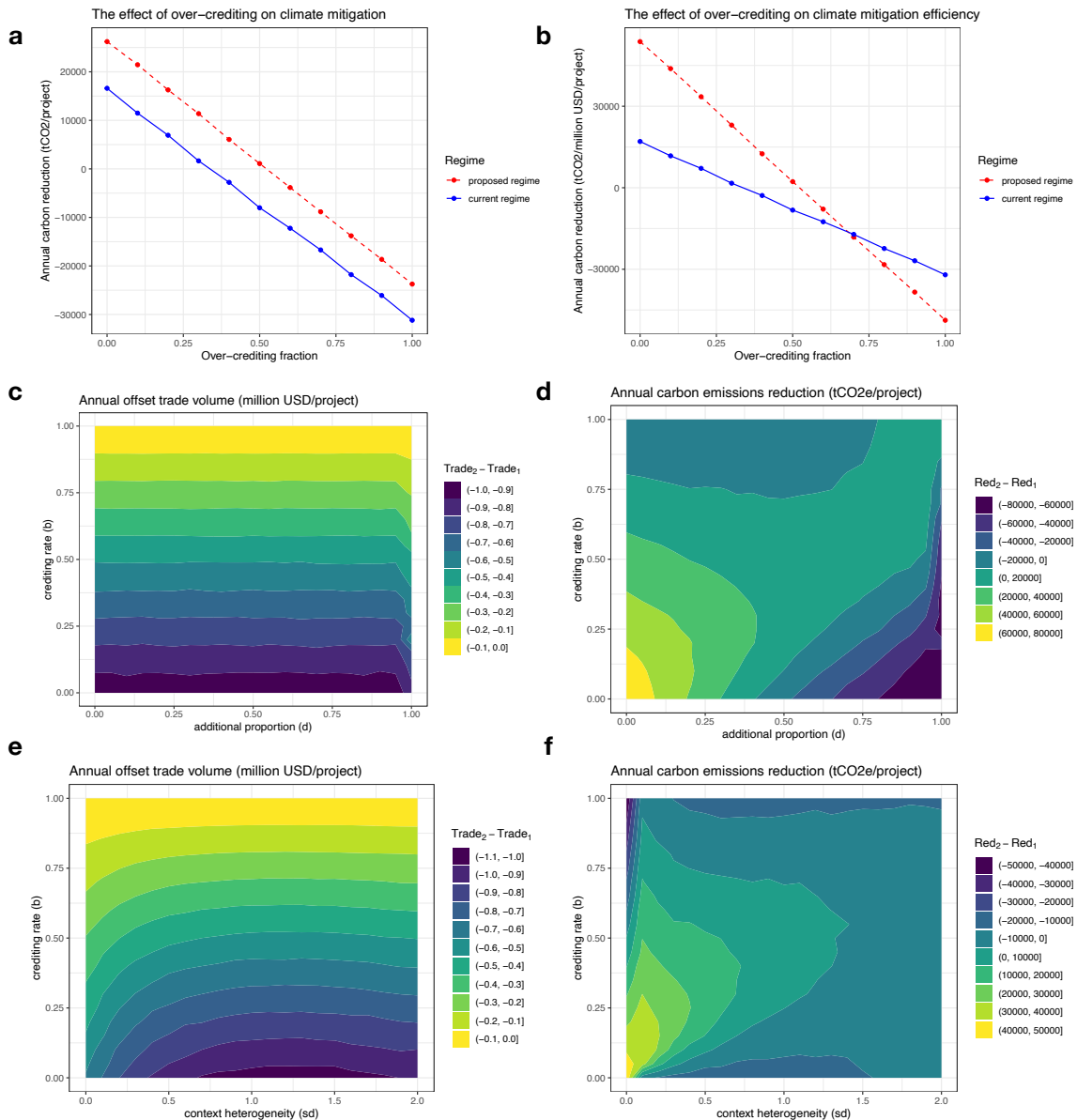
214

### 215 **Sensitivity analysis to project characteristics**

216 Lastly, we examine the performances of the two regimes under different project  
217 characteristics, that is, for synthetic project pools where the proportion of additional projects  
218 is not fixed at 50%, keeping the regulation quality constant and the same as in the main  
219 scenario. The results confirm that trading volumes are a direct function of the crediting rate:  
220 the higher the crediting rate, the larger the trade volume (Fig. 4c). Aggregate carbon  
221 emissions reductions tend to be larger under the proposed regime when the crediting rate is  
222 close to the real additional proportion in the synthetic project pool (Fig. 4d).

223 As well as different additional proportions, project pools may differ in terms of  
224 heterogeneity. To analyse this, we study changes in the standard deviation of project IRRs  
225 without credits. Calibration on Chinese wind projects created a relatively homogenous  
226 synthetic project pool with a standard deviation in IRRs of 0.57. We introduce greater  
227 heterogeneity in project characteristics by varying the standard deviation from 0 to 2 in  
228 increments of 0.1. The results show that the trade volume decreases slightly as the context  
229 becomes more heterogenous (Fig. 4e). Crucially, the performance of the proposed regime  
230 deteriorates when the standard deviation of project IRRs increases to 1.5 compared to the  
231 current regime (Fig. 4f). This indicates that controlling the heterogeneity within the pool of  
232 projects assessed is a prerequisite to adopt the proposed approach; it benefits from  
233 reasonable categorisation, which relies on careful disaggregated analysis across contexts.

234 Overall, our sensitivity analysis shows that the proposed regime robustly outperforms  
235 current practice. First, the proposed regime reduces emissions more effectively under most  
236 scenarios, unless the regulation on current additionality tests is unbiased and very accurate.  
237 Second, it is more resilient towards over-crediting issues with a context-based crediting rate  
238 to shave off the over-credited fraction. Third, even applying high-quality regulation, setting a  
239 reasonable baseline crediting rate near the actual additional proportion can still contribute to  
240 larger carbon emission reduction with smaller trade volume.



242

243 **Figure 4. Sensitivity analysis with respect to over-crediting and project pool**  
 244 **characteristics**

245 **a**, Annual carbon emission reduction (measured in tCO<sub>2</sub>e per project) in response to different over-  
 246 crediting fractions under the two regimes (blue solid line: current regime, red dashed line: proposed  
 247 regime). **b**, Annual carbon emission reduction per million USD in response to different over-crediting  
 248 fractions under the two regimes. **c**, Contour plot for annual trade volume given the regulatory accuracy  
 249 of 2.5 and the acceptance rate of 0.9. **d**, Contour plot for annual carbon emission reduction given the  
 250 regulatory accuracy of 2.5 and the acceptance rate of 0.9. **e**, Contour plot for annual trade volume  
 251 given the regulatory accuracy of 2.5, the acceptance rate of 0.9 and the real proportion of 0.5. **f**,  
 252 Contour plot for annual carbon emission reduction given the regulatory accuracy of 2.5, the  
 253 acceptance rate of 0.9 and the real proportion of 0.5.

254

## 255 **5. Discussion**

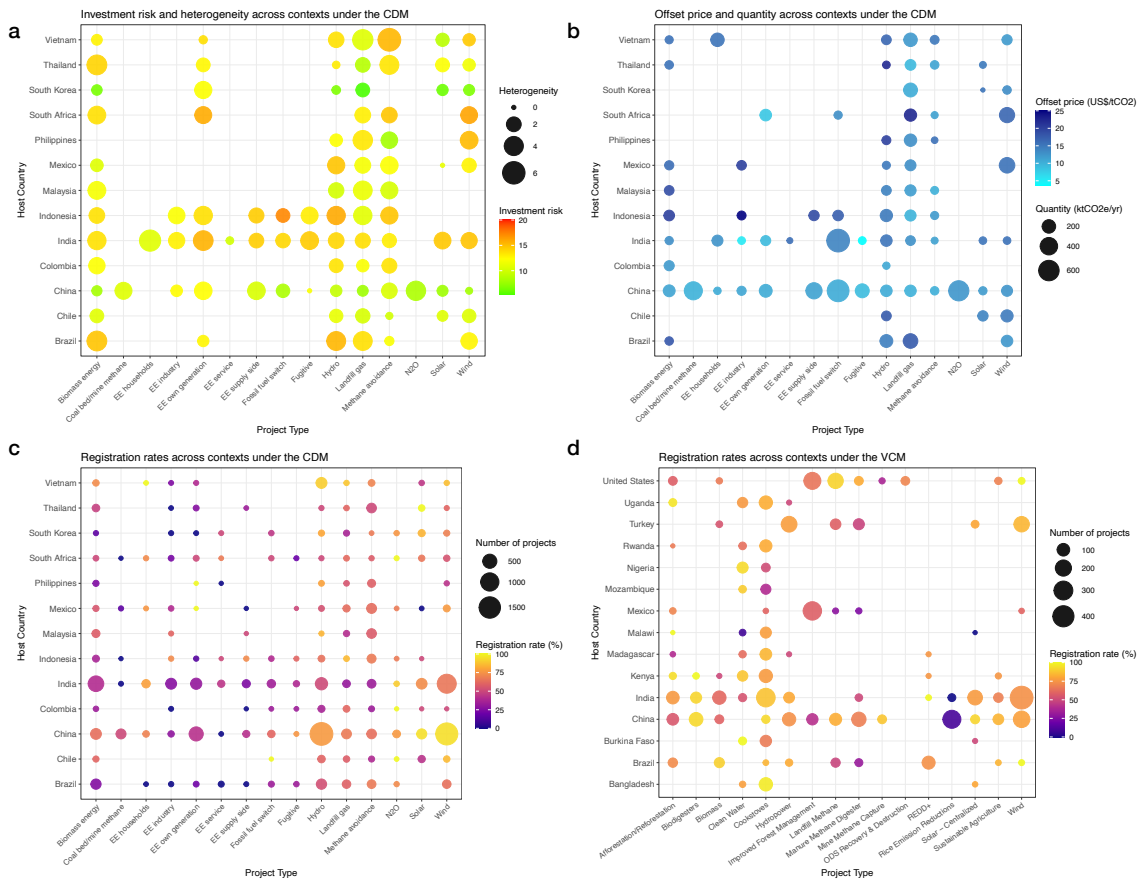
256 Additionality is essential for carbon offset projects to create genuine climate benefits that  
257 would not occur otherwise<sup>29</sup>. Although the existing certification regimes adopt a variety of  
258 additionality tests to assess individual projects, extant research insights for climate  
259 mitigation<sup>30–32</sup> and credit mechanisms<sup>33,34</sup> have mostly been neglected. Carbon offsetting has  
260 rightly been criticised for the widespread overestimation of climate benefits associated with  
261 over-crediting and inaccurate baselines<sup>19,35,21</sup>. There is a high likelihood of regulatory  
262 mistakes under a regime based on case-by-case testing relying on human judgement.

263 The temptation is to either add further complexity to the approval process or discard  
264 offset markets altogether. However, our simulations suggest that a regulatory regime based  
265 on standardised context-based positive lists and partial credit allocation rules would  
266 materially reduce the problem of non-additional carbon offset credits, alongside other  
267 improvements.

268 Our proposed additionality regime goes beyond the artificial dilemma that projects must  
269 either be judged 0% or 100% additional, with strict thresholds likely distorting incentives<sup>36,37</sup>,  
270 and more accurately reflects the reality that regulators are making a probabilistic judgment  
271 based on imperfect and incomplete information. Additionally, this proposed dynamic context-  
272 based regime can effectively take investment risks, non-additionality risks, domestic policies  
273 as well as oversight of host countries into consideration<sup>26</sup> and allow for timely update based  
274 on disaggregated industry analysis. When controlling for context heterogeneity through  
275 classification and varying standardised crediting rates, this alternative additionality regime  
276 outlines a novel pathway to simplify current practice into an eligibility check and a credit  
277 allocation rule, and in the meantime improve the environmental integrity of carbon credits.

278 To adopt the proposed regime, regulators would need to generate context-based positive  
279 lists and standardised crediting rates by analysing historical data, and collecting insights from  
280 industry experts through interviews and surveys<sup>27</sup>. To test the feasibility of this task, we  
281 provide some disaggregation and contextual analysis of historical data to reflect the  
282 investment risk and context heterogeneity (Fig. 5a), credit price and quantity (Fig. 5b), and  
283 registration rates (Fig. 5c, 5d) across host countries and project types under the CDM and  
284 the VCM.

285



286

287 **Figure 5. Historical carbon offset project characteristics by host country by project**  
 288 **type**

289 **a**, Investment risk (measured by mean of benchmark IRR) and heterogeneity (measured by standard  
 290 deviation of benchmark IRR) under the CDM. **b**, Offset credit price (US\$/tCO<sub>2</sub>) and quantity (GHG  
 291 reduction ktCO<sub>2</sub>e/yr) under the CDM. **c**, Registration rates (%) across contexts under the CDM. **d**,  
 292 Registration rates (%) across contexts under the voluntary carbon market (VCM). Here, EE refers to  
 293 energy efficiency; ODS refers to ozone depleting substances, REDD+ refers to reducing emissions  
 294 from deforestation and forest degradation.

295

296 Reflecting regional disparities in climate investments<sup>38</sup>, benchmark IRRs were generally  
 297 higher and more varied in less developed countries (e.g., India, Indonesia, Brazil, and South  
 298 Africa) associated with higher investment risks, compared to South Korea, China, and Chile.  
 299 Yet registered projects such as landfill gas in Brazil and South Africa, and biomass energy  
 300 and energy efficiency in Indonesia and Mexico reported higher credit prices. This indicates  
 301 that the market price may be influenced more by the quality of credits than the investment  
 302 risk level.

303 The substantial differences in registration rates suggested that regulators were more  
 304 likely to reject projects within certain contexts as a way to mitigate perceived non-

305 additionality risks. As such, inconsistent and biased judgments over non-additionality risks  
306 across regulators have introduced significant uncertainty into the assessment of individual  
307 projects. Notably, the registration rate of Brazil's biomass projects under the CDM was only  
308 26%, yet 90% under the VCM. Despite the fact that most CDM data dated back 15 years, the  
309 regulatory bias issue likely persisted in recent VCM projects. The fragmented governance of  
310 different carbon offset registries highlighted the urgent need for coordination, standardisation,  
311 and transparency to ensure environmental integrity<sup>39</sup>.

312 As we show that the proposed regime is more effective when the context is more  
313 homogenous (Fig. 4f), some contexts (e.g., wind, hydro, and biomass energy in South Korea  
314 and China, EE services in India, methane avoidance in Brazil and Chile) that have  
315 accumulated a considerable size of data sample showing a small standard deviation of the  
316 hurdle rate, fit the proposed regime better than others (Fig. 5a). On the other hand, the  
317 higher the registration rate, the larger proportion of additional projects the regulator would  
318 perceive. As a crediting rate slightly lower than the proportion of additional projects helps  
319 achieve the best outcomes (Fig. 3g, 3h, 3d), the proposed regime can apply higher crediting  
320 rates for contexts with higher registration rates (e.g., solar in Thailand, cookstoves in  
321 Bangladesh, clean water in Burkina Faso, biodigesters in Kenya) accordingly (Fig. 5c, 5d).  
322 For some project types, especially related to emerging clean technologies, that are newly  
323 added to the methodology of carbon credits and lack historical data, insights from industry  
324 experts are necessary in this case.

325 Our analysis has several limitations. First, since the voluntary registry offsets database  
326 does not disclose financial parameters of submitted projects, we calibrate our model  
327 parameters on one context only (Chinese wind farms) where most CDM projects were  
328 registered prior to 2012. Yet, the construction of project pools can further integrate recent  
329 VCM projects to capture the characteristics of current contexts and their changes. Second,  
330 the available databases are an incomplete set of all potential projects, because they only  
331 cover those that applied to generate credits, leaving those that did not apply unobserved.  
332 More comprehensive context analysis is expected to enhance the reliability of simulation  
333 results. Third, we assume that all project developers game the system to the same extent,  
334 but the situation is more complex in the real world. This demands more case studies to  
335 investigate the incentives of various stakeholders and the profitability of clean investments  
336 within one context.

337

## 338 **6. Methods**

339 Our simulation model has three components. The first component is a synthetic pool of  
340 potential offset projects, from which projects are drawn randomly. The second component  
341 models the decision of project developers, who choose whether a project should be  
342 submitted for offset accreditation or not. The third component models the regulator's  
343 response, who can either reject or approve the project under the current regime, or set a  
344 baseline crediting rate under the proposed regime.

345 We start by constructing a synthetic project pool with a full set of potential offset projects,  
346  $n \in N$ . Each potential project has its own characteristics including initial investment cost ( $C_0$ )  
347 achievable offset quantity ( $Q$ ) and price ( $P$ ), and two internal rates of return, IRR ( $r_0, r_1$ ) one  
348 without and one with credit revenues ( $CR$ ); these project features may correlate with each  
349 other. To make this artificial project pool as realistic as possible, we calibrate the parameters  
350 and their correlations on historical data from CDM wind farm projects in China. Importantly,  
351 we introduce a bias term in IRR ( $g$ ), i.e. the difference in reported and actual IRRs,  $g = R_0 -$   
352  $r_0$ , to measure the gaming behaviours.

353 We start by constructing a synthetic project pool, which includes the full set of potential  
354 offset projects,  $n \in N$ . Each potential project has its own characteristics including initial  
355 investment cost ( $C_0$ ) achievable offset quantity ( $Q$ ) and price ( $P$ ), and internal rates of return,  
356 IRR ( $r_0, r_1$ ) without and with credit revenues ( $CR$ ). These project features may correlate with  
357 each other. To make the synthetic project pool as realistic as possible, we calibrate the  
358 parameters and their correlations on historical data from CDM wind farm projects in China.  
359 To measure the gaming behaviours, we introduce a bias term in IRR ( $g$ ), i.e. the difference in  
360 reported and actual IRRs. More details are presented in the section 5 of Supplementary  
361 Information.

362 The decisions by project developers and the regulator are made endogenously as a  
363 function of project characteristics. Additional details are provided in the section 4 of  
364 Supplementary Information.

365 We assume project developers maximise profit. They are guided by a payoff function,  $\pi$ ,  
366 which reflects either the current offsetting rules or the proposed rules. Under both regimes  
367 and for each candidate project, the developer has to make two decisions: (1) whether to  
368 pursue the project ( $s_1 = 1$ ) or not ( $s_1 = 0$ ); and (2) whether to apply for carbon credit status  
369 ( $s_2 = 1$ ) or not ( $s_2 = 0$ ). In the current regime, the developmental fee ( $c_d$ ) and the validation  
370 fee ( $c_v$ ) are already sunk costs when entering the registration stage for additionality testing; A  
371 key difference in the proposed regime is that project developers are exempt from  
372 developmental and registration fees, and only need to check whether they satisfy the  
373 eligibility criteria in positive lists. The registration fee ( $c_r$ ) is the same under two regimes.

374 Unlike the decisions by the project developer, which are known with certainty, there is an  
375 element of randomness in regulatory decisions due to information asymmetries. The  
376 regulator needs to judge whether a project is deemed additional ( $q = 1$ ) or not ( $q = 0$ ) and  
377 decides whether to accept ( $ac = 1$ ) or reject ( $ac = 0$ ) the application under the current  
378 regime. A rational regulator will speculate the gaming behaviours and estimate the actual  
379 data from the submitted data with a probability of being fabricated. We assume that the policy  
380 hurdle rate determined by the regulator's belief in the (unobserved) additional proportion  
381 within one sector in one country can be reflected by the observed acceptance rate ( $AC \approx p$ ).

382 Practically, regulators must use their knowledge and experience to determine a certain  
383 value as the policy hurdle rate and reject IRR-above-policy-hurdle-rate projects. At a result,  
384 the regulation can be unbiased or too lenient (strict) if the policy hurdle rate is larger (smaller)  
385 than the real hurdle rate. The inclusive (exclusive) regulation will allow for more false  
386 acceptances (rejections). In addition, when the actual IRR without credits of a project is near  
387 the real hurdle rate, it's more difficult for the regulator to make a correct decision so the  
388 regulation will be inaccurate when the tests fail to distinguish whether or not a project has an  
389 IRR above the policy hurdle rate.

390 Since the regulator is more likely to reject a project as its profit goes up, we stipulate that  
391 the probability of a successful additionality decision ( $q$ ) is negatively correlated with the  
392 actual IRR without credits ( $R_0$ ). We specify these properties through an inverse of a logistic  
393 function with a range between 0 and 1 (see Supplementary Information Eq. 23). The simple  
394 model of regulatory performance is then used to simulate project outcomes and compare the  
395 annual financial flows (credit trade volume), the emission reductions and the climate  
396 mitigation efficiency between the two regimes (see Supplementary Information Eq. 25-29).

397 A review of policy and the extant literature, a descriptive summary of historical data, the  
398 simulation model calibration, sensitivities and caveats are discussed in detail in  
399 the Supplementary Information.

400

## 401 **7. Data availability**

402 The data underlying the results reported here are freely available online from the CDM  
403 Pipeline (<https://unepccc.org/cdm-ji-pipeline/>) and the Voluntary Registry Offsets Database  
404 (<https://gspp.berkeley.edu/berkeley-carbon-trading-project/offsets-database>).

## 405 **8. Code availability**

406 R scripts for replicating the results presented in all the figures and tables are publicly  
407 available ([https://github.com/Ruanancy1998/carbonoffsets\\_additionality.git](https://github.com/Ruanancy1998/carbonoffsets_additionality.git)).

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