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# Monitoring, reporting and verifying emissions in the climate economy

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## Abstract

This monitoring, reporting and verification (MRV) of greenhouse gas emissions is important for carbon pricing and management mechanisms. Here we review peer-reviewed articles and 'grey literature' related to the costs of MRV. A substantial part of the literature is the regulatory texts of the fifteen most important carbon pricing and management mechanisms currently implemented. Based on a comparison of key criteria such as the scope, cost, uncertainty and flexibility of procedures, we conclude that conventional wisdom on MRV is not often promoted in existing carbon pricing mechanisms. Quantification of emissions uncertainty and incentives to reduce this uncertainty are usually only partially applied, if at all. Further, the time and resources spent on small sources of emissions would be expected to be limited. Although provisions aiming at an effort proportionate to the amount of emissions at stake – 'materiality' – are widespread, they are largely outweighed by economies of scale: in all schemes, MRV costs per ton are primarily driven by the size of the source.

This paper reviews the monitoring, reporting and verification (MRV) of greenhouse gas emissions as it is practiced in the climate economy and is based on the material produced for an upcoming book on the same topic<sup>1</sup>. 'Climate economy' is here extended to any incentive for a set of economic stakeholders to reduce their greenhouse gas emissions. The incentive is often a hard economic one (e.g. a carbon tax), but it can take softer forms, such as reputational incentives attached to meeting an emissions reduction pledge for a country, local government or a company, or branding incentives derived from environmental labeling (e.g. carbon footprint of products). This scope corresponds to what Ascuri and Lovell<sup>2</sup> refer to as the 'market-enabling' frame for carbon accounting, although this largely overlap with the 'political frame' when jurisdictions such as countries or cities are the object of the carbon pricing and/or management mechanism (CPM).

Fifteen schemes are reviewed here (Table 1). The selection criteria were primarily designed to cover the most important existing CPMs. The importance of each scheme was assessed in terms of number of entities concerned, amount of emissions concerned, longevity of the scheme, amount of money at

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38 stake, etc. Priority was given to compliance schemes; that is, schemes designed by a regulator who  
39 issues clear and mandatory guidelines and who has some means of enforcing the guidelines. This  
40 unique set of guidelines allows us to state what are the existing MRV requirements rather than  
41 describe how some entities proceed in terms of MRV within a flurry of different approaches. Within  
42 the schemes of lesser importance, priority was given to those which presented an original feature  
43 (e.g. the inclusion of the waste sector in the Australian carbon pricing mechanism). Forty-one  
44 systematic questions were asked for each scheme (see supplementary materials), and the relevant  
45 literature – peer-reviewed articles, reports, regulatory texts, regulatory impact assessment, and so  
46 on – was reviewed to help provide answers. In the tables and figures, project scale CPMs are grouped  
47 or duplicated by type (e.g. N<sub>2</sub>O emissions in agriculture) which is why the number of categories do  
48 not always add up to fifteen.

## 49 1. Definitions

50 **Monitoring** covers the *scientific* part of the MRV process. It involves getting a number for each  
51 variable part of the equation which results in the emissions estimate. This ranges from direct  
52 measurement of gas concentration using gas meters to the recording of proxies such as fuel  
53 consumption based on the bills of a given entity. The use of proxies is common practice, through the  
54 general equation:

55

56 activity data x emission factor = greenhouse gas emissions (Eq. 1)

57

58 where activity data is the proxy (eg. fuel consumption, heads of cattle) and emission factor is the  
59 conversion factor (eg. tons of CO<sub>2</sub> per liter of burnt fuel, tons of CO<sub>2</sub>e per animal per year). Both  
60 activity data and emission factor change over time and hence need to be monitored. Activity data  
61 nevertheless tends to vary more frequently than emission factors.

62

63 **Reporting** covers the *administrative* part of the process. It involves aggregating and recording the  
64 numbers, explaining how you came up with them in the requested format, and communicating the  
65 results to the relevant authority, such as the regulator or the top management of the company.

66 The purpose of **verification** is to detect errors resulting from either innocent mistakes or fraudulent  
67 reporting. It is usually conducted by a party not involved in monitoring and reporting who checks that  
68 these two steps were conducted in compliance with the relevant guidelines.

## 69 MRV scale

70 Although not plentiful, the existing literature on MRV in climate economics agrees on three possible  
71 scales which greatly influence how MRV can be conducted: territory, entity and project<sup>3-5</sup>.

72 The **territorial scale** includes all emissions occurring within a given geographic area such as a country  
73 or an administrative region. All activities and entities operating within the area are considered.  
74 Examples include national greenhouse gas inventories supervised by the United Nations, regions or  
75 cities which have committed to a voluntary or statutory cap on emissions, and jurisdictions engaged  
76 in a program for Reducing Emissions from Deforestation, forest Degradation and other changes in  
77 forest carbon stocks (REDD+). Although the last example is restricted to forest-related emissions, it  
78 still includes all those occurring within the jurisdiction, no matter the activity or entity responsible for  
79 them.

80 The **entity scale** includes emissions related to the operations of a given public or private entity. In a  
81 few cases, all the emissions of the entity are included, such as businesses participating to the Carbon  
82 Disclosure Project or entities mandatorily reporting their emissions under the 'Grenelle 2' French

83 environmental law enacted in 2010. Most often however, only the emissions corresponding to a  
84 restricted set of operations are included. This is the case of mechanisms putting an explicit price on  
85 carbon such as the European Union Emissions Trading System, the Australian carbon tax or the  
86 Californian Emissions Trading Scheme. In those cases, the MRV occurs at the scale of individual  
87 facilities.

88 The **project scale** includes emissions stemming from specific emissions reduction projects. These  
89 projects are often focused on a given activity, such as destroying an industrial gas or spreading  
90 efficient cookstoves. The number of entities and the geographic area considered is then adapted *ad*  
91 *hoc* to the considered activity. The main example is offset projects, be they certified by the dominant  
92 Clean Development Mechanism of the United Nations, or by other standards such as the Verified  
93 Carbon Standard or the Gold Standard. As opposed to the two other scales, the MRV of greenhouse  
94 gas emissions always comes together with the MRV of greenhouse gas emissions reduction at the  
95 project scale: both the project emissions and its counter-factual – or baseline – emissions are  
96 monitored, reported and verified at the same time, and along the same rules.

### 97 **Dealing with uncertainty**

98 The last important concept for this review is the **uncertainty** associated with emissions MRV. This  
99 concept involves a flurry of terms which are not always understood in the same manner. We adopt  
100 the terminology of the IPCC<sup>6</sup>: uncertainty corresponds to the difference between the estimate and  
101 the actual value. Hence, it covers the two types of errors that are commonly distinguished:  
102 systematic errors or bias that decrease the **accuracy** of the estimate (e.g. miscalibrated gas meter,  
103 unit error in the reporting) and random errors which decrease the **precision** of the estimate (e.g.  
104 sampling error, errors of copy in the reporting). In monitoring, lack of precision and accuracy can  
105 both lead to uncertain estimates but only the first can be dealt with by increasing the number of  
106 samples. Bias can only be reduced by monitoring and reporting the same source of emissions with a  
107 change in the method. In reporting, both types of errors can be reduced through quality control and  
108 verification.

### 109 **MRV trade-offs**

110 Scale and uncertainty lead to the two necessary trade-offs in the MRV of greenhouse gas emissions,  
111 as explained by Cochran<sup>3</sup>: *cost vs uncertainty* and *information relevance vs comparability*. The trade-  
112 off between **cost and uncertainty** is one of the key threads of this review. For each CPM considered,  
113 we identify whether flexibility provisions are in place to adapt uncertainty requirements to the cost  
114 incurred by stakeholders. These provisions may take the form of **de minimis thresholds**, that is  
115 threshold levels of emissions under which monitoring and reporting are not required, or '**materiality**  
116 **thresholds**', that is threshold levels of errors under which errors are tolerated during verification.  
117 They can also take a more continuous form, for example by increasing the cost of compliance or  
118 discounting the benefits from carbon credits in proportion to the uncertainty of monitoring.

119 The second trade-off between **information relevance and comparability** comes from the difference  
120 in information needs from case to case. A country with only a couple of trees such as Monaco will see  
121 the quantification of emissions from its forestry sector as a complete waste of resources when it  
122 comes to designing climate mitigation policies. But Canada or Brazil may not see it that way.  
123 However, letting each country choose the sources it monitors, the method it uses to report them and  
124 the format under which all this is reported would greatly hamper the comparison of emission levels  
125 between countries. The same goes for cities, companies and offset projects depending on their  
126 specific context and needs.

127 In a nutshell, five cross-cutting questions are asked on the schemes being reviewed:

128 (1) what are the requirements pertaining to monitoring uncertainty?

129 (2) What are the costs for entities to meet these requirements?

130 (3) Is a flexible trade-off between requirements and costs allowed?

131 (4) Is requirements stringency adapted to the amount of emissions at stake (materiality)?

132 (5) What balance between comparability and information relevance?

## 133 **2. MRV requirements across schemes**

134 The first cross-cutting question – what are the MRV requirements? – is too large to be answered in a  
135 synthetic way. This section thus focuses on two components of this question that have a major  
136 impact on MRV costs: requirements pertaining to third-party verification and those pertaining to  
137 monitoring uncertainty.

### 138 **Verification requirements are broadly similar across the board.**

139 Most CPMs impose a verification of the reports by an independent third-party. Verification  
140 requirements are broadly similar across CPMs (Figure 1):

141 first, the third party must be accredited by the regulator for GHG emissions audits and this  
142 accreditation tends to be sector-specific;

143 second, the third party must assess whether the methods used and the reporting format comply with  
144 the relevant guidelines;

145 third, the third party must assess the accuracy, i.e. the absence of bias, of the reported figures;

146 fourth, the regulator is allowed to question the opinion of the auditor, but seldom does so;

147 and fifth, the third party tends to be paid directly by the verified entity. Although this creates a  
148 potential conflict of interest, the risk of losing the accreditation is a much stronger incentive and  
149 keeps auditors from being complacent with their client<sup>7</sup>. Random verification of a few entities only –  
150 as is the case for small projects under the Gold Standard and for small installations under the  
151 Australian Carbon Pricing Mechanism – is an exception: the auditor is then paid by the regulator. The  
152 verification of national GHG inventories under the UNFCCC is also not directly paid by the countries  
153 under review.

154 Some details may differ (Table S1). Verification frequency is one example: it tends to be annual for  
155 most entities at site/company scale whereas it is variable – up to the project proponent – at project  
156 scale. The emphasis put on individuals also varies across schemes: UNFCCC accredited reviewers act  
157 in their own name, and so do auditors in California and Australia. Under the EU ETS and the CDM  
158 however, it is firms rather than individuals which are accredited, although one of the key criteria to  
159 obtain accreditation is of course to secure individual competence either internally or through long-  
160 term subcontracting. Note that Member States have some leeway on the accreditation procedures  
161 for EU ETS verification. As a result, and although most countries accredit firms, some accredit  
162 individuals.

163 The only schemes which stray away from these general observations are the schemes with little  
164 financial stakes: sub-national inventories and company level footprints. The latter are nevertheless  
165 often verified: verification is incited under the Carbon Disclosure Project – verified respondents get a  
166 higher score within their transparency rating – and it is even mandatory for some companies under  
167 the French Grenelle II law (Article 225). Yet these verifications are peculiar: what matters are the  
168 reporting procedures of the company – do they ensure the internal consistency and “fairness” of the  
169 reported figures – rather than the accuracy and precision of the reported figures. In addition, the  
170 requirements on the expertise of the third party on GHG emissions is rather limited in these  
171 schemes: indeed, companies tend to use their financial auditors, which saves time as they are  
172 already familiar with the company structure and its accounts.

173 **Requirements on monitoring uncertainty are seldom comprehensive.**

174 Sources of monitoring uncertainty are multiple. When calculation methods are used, there are as  
175 many sources of uncertainty as there are variables and parameters used in the calculation. Methods  
176 exist to combine the uncertainty from all sources in order to produce a comprehensive estimate (see  
177 for example GHG Protocol<sup>8</sup> or IPCC<sup>6</sup>). Yet, CPMs seldom set a requirement on the overall uncertainty  
178 of a given source. The case of direct measurement in the EU ETS is a notable exception. The EU ETS  
179 and a few offset project methodologies get close, as quantitative requirements are set on most  
180 sources of uncertainty – activity data and emission factors – involved in the calculation method. Most  
181 schemes also require a minimum calibration frequency when instruments are used. This frequency is  
182 often borrowed from existing national or international standards. The impact of calibration  
183 requirements on the actual uncertainty may be significant but is difficult to quantify across sectors  
184 and schemes<sup>9</sup>.

185 However, the majority of CPMs only set quantitative requirements on a few sources of uncertainty  
186 (Figure 2, Table S2). When financial stakes are low – that is when mechanisms are primarily about  
187 accounting and tracking rather than directly pricing carbon, as in most jurisdictional schemes or for  
188 company-level footprint, the requirements are either qualitative – e.g. using a context-specific  
189 emission factor for major sources – or non-existent. Hence, most CPMs only exert a partial control  
190 over the uncertainty that is reported.

191 **3. Incentives to reduce monitoring uncertainty**

192 **Conservativeness: gap between principle and practice.**

193 MRV concepts and principles are often presented without significant attention to how they are  
194 applied in practice. Conservativeness perfectly illustrates this gap between theory and practice.

195 ‘*Conservativeness*’ means that when the data is uncertain, a conservative value should be used so  
196 that emissions are not underestimated. This principle is often interpreted as an incentive to reduce  
197 monitoring uncertainty, often by adding one or two standard deviations to the estimate. If it were so,  
198 *conservativeness* would indeed provide an implicit incentive to reduce uncertainty.

199 But in practice, most of the rules in CPMs do not discourage the use of default values or the  
200 uncertainty of the monitoring method (Table S2). For example, the UNFCCC guidelines for national  
201 GHG inventories allow for any type of uncertainty range, provided that the estimate is not biased<sup>6</sup>.  
202 The EU ETS limits the uncertainty of some elements but does not reward further uncertainty  
203 reduction as long as the threshold is met<sup>10</sup>.

204 The CDM Executive Board has yet to clarify and systematize its application of the conservativeness  
205 principle, except in the case of surveys and samples<sup>11</sup>. Although some CDM tools and methodologies  
206 are already awarding fewer credits in proportion to reported uncertainty, this is not systematic.  
207 Many CDM methodologies provide an implicit incentive to reduce uncertainty by using conservative  
208 default values for some parameters or variables<sup>9</sup>. Yet, these incentives remain limited in the CDM for  
209 three reasons<sup>12</sup>:

210 (1) in most cases, conservativeness only concerns one or two parameters whereas the number of  
211 parameters involved in the calculation often exceeds ten<sup>13</sup>. These parameters were possibly chosen  
212 during the validation of the methodology as the most influential ones based on expert judgment. But  
213 this leaves out many sources of uncertainty whose importance has not been assessed in a systematic  
214 manner;

215 (2) conservativeness is only applied to the most uncertain option out of three or four possible  
216 monitoring methods (e.g. UNFCCC<sup>14</sup>);

217 and (3), an alternative method to the conservative default value is not systematically offered in the  
218 methodology. When this happens, a project proponent wishing to be rewarded for further reducing

219 uncertainty will have to appeal to the Methodology Panel to revise the methodology. The resources –  
220 time and technical – necessary to undertake such a step represent a significant barrier.

#### 221 **Conservativeness is not a panacea.**

222 Nevertheless, there may be good reasons not to be conservative when monitoring emissions. One is  
223 that conservativeness gives a competitive advantage to larger installations or entities where  
224 economies of scale make it economically feasible to use fewer default values and more precise  
225 monitoring methods (see Section 4.4). In the EU ETS, this would exacerbate the distortion created by  
226 MRV costs and likely explains why the regulator has abstained from embedding conservativeness in  
227 the Monitoring and Reporting Regulation (MRR). In California, the default emission factor applied to  
228 imported electricity is rather generous: it corresponds to a clean gas power plant<sup>15</sup>. This is the very  
229 contrary of being conservative, but it was likely necessary to avoid judicial proceedings from  
230 neighbouring states for breaching the constitutional right to free interstate commerce<sup>16</sup>. The EU  
231 faced a similar dilemma when setting an emission factor to oil produced from Canadian tar sands  
232 under the Fuel Quality Directive<sup>17</sup>. In offset schemes however, the risk of adverse selection<sup>20</sup> offers a  
233 strong argument in favour of conservativeness.

#### 234 **Should there always be an incentive to reduce uncertainty?**

235 Although generally rare, incentives to reduce monitoring uncertainty are embedded in a few number  
236 of CPMs (Figure 3, Table S3). Some offset project methodologies for example discount the amount of  
237 credits issued in proportion to the overall monitoring uncertainty (e.g. VCS VM012 on improved  
238 forest management<sup>18</sup>) or in proportion to the uncertainty of one component of the estimate (e.g.  
239 leak flow rate in CDM AM0023 on fugitive emissions<sup>19</sup>).

240 These provisions may make sense in offset schemes which are vulnerable to adverse selection<sup>20</sup>:  
241 project proponents who benefit from the error – because their monitored emissions reductions are  
242 by chance above the true value – are more likely to join than those whose emissions reductions are  
243 underestimated. This selection bias eventually produces an overestimate in the aggregated total,  
244 despite the random nature of each individual error.

245 However, economic theory and literature do not provide unconditional support for incentives to  
246 reduce uncertainty<sup>21</sup>. In general, uncertainties tend to balance out rapidly with an increasing number  
247 of emission sources and therefore tend to be of little concern. Exceptions may emerge in specific  
248 cases of information asymmetry or when a scheme encompasses only a few large sources.

249 Indeed, the regulator should in theory worry more about bias than about precision. And in many  
250 configurations reducing the reported uncertainty does not reduce the risk of bias. To reduce the risk  
251 of bias, the *expert judgment* of independent and competent auditors likely remains the best suited  
252 approach. A likely costly alternative would be to require a second estimate obtained from a different  
253 and independent method.

254 In practice, there is no clear consensus among regulators on the importance of monitoring  
255 uncertainty. The European Commission cites the large uncertainty of waste emissions as one of the  
256 main reasons to keep the sector outside the EU ETS<sup>22</sup> whereas it did not visibly hinder Australia from  
257 including it in its CPM. Based on economic theory and the existing literature on this topic alone, it is  
258 not possible to clearly determine “who made the best choice”.

#### 259 **4. Economies of scale**

260 Economies of scale are the dominant feature of MRV costs, at least when these costs are compared  
261 on a *per ton of CO<sub>2</sub>e* basis. These economies have an automatic component: the division of a given  
262 cost by a larger denominator; and an intended one: regulation, mandatorily applied to a large  
263 number of sources and entities, must not impose too heavy a burden on the complying entities as  
264 these cannot opt-out.

265 **MRV costs decrease with the comprehensiveness of the perimeter.**

266 The larger and the more comprehensive a scheme, the lower the MRV costs. Jurisdictional schemes  
267 tend to cover all sources within a jurisdiction which adds up to a large amount of GHG emissions. As  
268 a result, they exhibit much lower MRV costs than other schemes per tCO<sub>2</sub>e (Table 1).

269 However, even when the amount of emissions per entity is comparable, for example between cap-  
270 and-trade schemes and offset schemes, comprehensiveness pushes MRV costs down (Figure 1, Table  
271 1). Indeed, company/site scale schemes tend to be mandatory and therefore to cover all entities that  
272 meet the inclusion thresholds (e.g. more than 20 MW for combustion installations under the EU ETS).  
273 As such, they must be especially careful with the costs they impose on regulated entities as these  
274 may distort the market (e.g. by putting higher costs on smaller entities) or even put unbearable  
275 burden on some firms<sup>9</sup>. Conversely, offset schemes in which participation is voluntary cannot  
276 bankrupt participating companies through MRV costs: if they are too high, companies simply do not  
277 participate. In addition, one of the interests of running an offset scheme is to reveal information on  
278 abatement opportunities, monitoring techniques and costs<sup>23,24</sup>. In this context, there is a rationale for  
279 leaning towards higher MRV costs in order to obtain better information. This is likely why offset  
280 schemes tend to exhibit higher MRV costs than cap-and-trade schemes (Table 1).

281 **MRV costs decrease with size.**

282 Even within the same scheme, MRV costs vary widely. A major factor explaining this variation is the  
283 size of entities (Figure 1). Indeed, fixed costs or costs that increase only slowly with entity size are  
284 numerous within MRV costs. Most monitoring and reporting costs are insensitive to size: a single  
285 monitoring report, methodology, project design document, national inventory report, etc. is needed  
286 per entity, no matter the amount it emits or reduces. In monitoring, the costs of a meter do not  
287 necessarily increase with the amount of material – electricity, fuel, gas, ... – that it measures.  
288 Similarly, sampling costs only increase in proportion to the square root of the sampled population.  
289 The same goes for verification: a large part of the workload is proportional to the amount of  
290 documentation provided, which is largely independent of the amount of emissions at stake.

291 After entity size, entity and sector complexity also plays into MRV costs<sup>25</sup>. A large refinery with  
292 hundreds of pipes, connections and gas streams is more difficult to MRV than a simple power plant  
293 with a couple of boilers. Similarly, two thirds of emissions from cement manufacture usually come  
294 from decarbonation. The monitoring of these *process emissions* involve a complex mass balance  
295 approach in addition to the more common and straightforward *activity data \* emission factor*  
296 approach used for energy consumption (the remaining third). Across schemes such as the EU ETS, the  
297 US EPA GHG Reporting Rule or the Californian ETS, refineries and cement factories face higher MRV  
298 costs: although cement factories are large and benefit from the aforementioned economies of scale,  
299 their monitoring costs under the US EPA GHG Reporting Rule are two times higher than the overall  
300 average on a *per tCO<sub>2</sub>e* basis<sup>26</sup>. Other types of industries are also impacted by their complexity such  
301 as electricity importers.

302 **The share of verification costs**

303 Contrary to conventional wisdom, verification is usually not the main part of MRV costs. On average,  
304 it varies between 0 and 50% of total MRV costs, with most schemes around 25% (Table 1).  
305 Verification costs are, however, mostly fixed costs. For smaller sources or entities, it can therefore  
306 take the lion's share of MRV costs, up to 80% of the total<sup>25</sup>. Moreover, to the contrary of monitoring  
307 and reporting costs, they cannot be internalized as the auditor must be an independent third party in  
308 most schemes.

309 **5. Materiality is commonly practiced but it does not outweigh economies of scale.**

310 Materiality is a concept which comes from the audit industry: an auditor should focus on the riskiest  
311 parts of what is being audited. In other words, one should pay more attention to larger numbers than

312 to smaller ones. Materiality has made its way into the verification procedures of most existing CPMs:  
313 accredited auditors can only invalidate a monitoring report when errors exceed a given threshold  
314 (e.g. 5% of total facility emissions in the Californian Emissions Trading Scheme). Nevertheless, the  
315 concept of materiality is not taken into account in most jurisdictional schemes, either because  
316 verification does not take place - as is the case for most sub-national inventories; or because the  
317 guidelines do not contain materiality provisions - which used to be the case for national GHG  
318 inventories (Figure 5, Table S4).

319 The concept of materiality could be extended beyond verification to monitoring and reporting: fewer  
320 resources should be spent on smaller sources than on larger sources, or on smaller facilities than on  
321 larger facilities. Many provisions exist in carbon markets and carbon taxes to balance stringency with  
322 the amount of emissions at stake: smaller facilities are usually not covered by the scheme, and even  
323 within the scheme, the uncertainty requirements or the reporting frequency is more lenient for these  
324 installations (Table S4). Yet, these provisions do not result in a level playing field. Economies of scale  
325 have the upper hand and larger facilities and offset projects end up with lower MRV costs per tCO<sub>2</sub>e  
326 (see Section 4.2). Finally, national GHG inventories still largely ignore the concept: the requirements  
327 are almost as stringent for Slovenia as they are for Germany. This is not to say that the existing  
328 “monitoring materiality” provisions are not useful: inclusion thresholds in particular are fundamental  
329 in limiting costs. The US EPA<sup>26</sup> assessed the effectiveness of a minimum threshold for inclusion in the  
330 perimeter of the regulation. Compared to 25,000 tCO<sub>2</sub>e yr<sup>-1</sup> threshold retained in the US, a 10,000  
331 tCO<sub>2</sub>e yr<sup>-1</sup> threshold would increase costs by 35% and cover only 1% more emissions. Conversely,  
332 decreasing the inclusion threshold to 100,000 tCO<sub>2</sub>e yr<sup>-1</sup> would save 23% of the costs and cover 2.5%  
333 fewer emissions.

## 334 6. Comparability often trumps information relevance

335 Comparability between entities reporting within the same CPM is usually a top priority. As a result,  
336 most mechanisms offer little leeway in terms of scope, level of source disaggregation and even  
337 monitoring method.

338 **Scope and level of source disaggregation.** All ETSs, taxes and offset projects define very precisely the  
339 gases and sources of emissions that are monitored. They also specify a common reporting format  
340 with a fixed separation of emissions sources. No leeway is left to the agent to adapt the scope or  
341 level of disaggregation to its own needs/constraints.

342 **Monitoring method.** ETSs, taxes and offset projects are very restrictive in terms of monitoring  
343 methods. Although a choice is usually offered to the agent, it is limited to a few options for which  
344 instruments and emissions factors are explicitly listed.

345 Schemes and management systems with limited constraints or financial stakes such as sub-national  
346 inventories and company-level footprint are the notable exceptions. Sub-national inventories follow  
347 a variety of guidelines, and the guidelines themselves are limited to accounting principles and  
348 suggested emissions factors. Each entity is then free to choose, within the guidelines or elsewhere,  
349 the detailed equations, monitored variables and instruments which best suits its needs and  
350 constraints. These entities are usually undertaking their MRV as a means to assess the effectiveness  
351 of their internal mitigation strategy. They therefore extensively use the large leeway offered by the  
352 relevant MRV guidelines to adapt the MRV procedures so that it suits their specific needs. Cochran<sup>3</sup>  
353 illustrates this phenomenon with the GHG inventories of cities. For company-level footprint, the  
354 trade-off is a little more balanced: the possibility for outsiders to compare companies between one  
355 another and the repeated use of the same consultants within a sector to put together company-level  
356 footprints tend to foster comparability on scope 1 – site-level emissions – and scope 2 – electricity  
357 use. For scope 3 – upstream and downstream emissions – however, company-level footprints remain  
358 very heterogeneous.

359 National greenhouse gas inventories under the UNFCCC lie somewhat in the middle. Countries must  
360 use a very strict reporting format which makes comparison easy. But the choice on monitoring  
361 methods is almost unlimited as countries are always offered the possibility to use a “Tier 3” method.  
362 “Tier 3” tends to be whatever model the country proposes as long as some general criteria – e.g. the  
363 model has been validated and published in the peer-reviewed literature – are met. Use of tier 3 is  
364 fairly uncommon given that even lower tiers already offer significant leeway concerning acceptable  
365 activity data and emission factors. As a result, reported figures are not strictly comparable between  
366 countries, although verification, and in particular the use of comparison tools provided by the  
367 UNFCCC Secretariat, keeps heterogeneity within acceptable limits.

## 368 7. Conclusion

369 Regarding our five cross-cutting questions, one can conclude that conventional wisdom on MRV is  
370 not often promoted in existing CPMs. One would intuitively encourage quantitative requirements on  
371 emissions uncertainty, together with an incentive to improve precision. Most often, this is only  
372 partially applied, if at all. Further, the time and resources spent on small sources of emissions would  
373 be expected to be limited. While this kind of ‘materiality’ is widespread, the softened rules for  
374 smaller sources are largely outweighed by economies of scale: in all schemes, MRV costs per ton are  
375 primarily driven by the size of the source. This is not to say that existing MRV rules are ill-devised.  
376 First, conventional wisdom may be wrong. Economic models indeed struggle to justify the usefulness  
377 of incentives to reduce monitoring uncertainty when dealing with many, small sources. Second, some  
378 phenomena, such as economies of scale, may be beyond the control of the regulator. MRV rules  
379 which create no market distortion are likely an unreachable grail.

380 These conclusions should be of great use to the scientific and industrial community currently  
381 designing new GHG monitoring technologies for use in existing CPMs:

382 (1) in most cases, there is no point in developing technologies with lower uncertainty than current  
383 practices because the rules do not value reduced uncertainty. In particular, the so-called  
384 ‘conservativeness’ principle often invoked to demonstrate the economic value of improved  
385 monitoring techniques is specific to a subset of CPMs – offset projects – and is not even applied  
386 systematically and consistently there;

387 (2) a more promising outcome awaits technologies which would meet the uncertainty requirements  
388 at a lower cost than what is achieved by current practices. The figures provided in this review on  
389 maximum uncertainty thresholds and MRV costs can be used as benchmarks by technology  
390 developers; and

391 (3) an alternative could be to lobby regulators for regulations with more comprehensive and more  
392 direct incentives to reduce monitoring uncertainty. This would likely be perilous as *top-down*  
393 regulations change slowly, in particular when there is no obvious rationale for the regulator to  
394 reduce monitoring uncertainty (see sections 3.2 and 3.3). *Bottom-up* CPMs such as offset projects are  
395 easier to amend, but their market size plummeted during the second half of 2012 without any clear  
396 prospect of recovery<sup>27</sup>.

397 Another cross-cutting conclusion to this study is that MRV rules significantly differ not only between  
398 “scales”, but also within them: the EU, Australia, California and Shenzhen have set different MRV  
399 rules in their respective site-level CPMs. Five thousand sites with emissions lower than 25,000 tCO<sub>2</sub>e  
400 per year are MRVed under the EU ETS while verification is only mandatory for sites emitting over  
401 125,000 tCO<sub>2</sub>e in Australia. The scope of the EU ETS is limited to heat and power generation and  
402 some industrial processes while the transportation sector, imported electricity, and waste are  
403 included in some of the other schemes. Shenzhen even double-counts emissions from electricity.

404 Will these MRV differences lock the world into incompatible frameworks with different carbon  
405 prices? Not necessarily. When considering whether to link two CPMs, mutual confidence in their

406 respective level of ambition will likely be pivotal for the regulators involved. And this confidence can  
407 be obtained with reliable MRV procedures on both sides even if they are not strictly equivalent. Only  
408 time will tell.

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- 613 Correspondence and requests for materials should be addressed to Valentin Bellassen  
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626 **10. Authors contributions**

627 V.B. designed the study, analyzed the pre-processed data and wrote the paper. V.B, M.A., E.A., A.B.,  
628 J-P.C., C.C., I.C., M.D., C.D., C.F., G.J., R.M., R.R, and I.S. gathered and pre-processed the raw  
629 materials. N.S. coordinated data collection.

630 **11. Tables**

631 **Table 1. MRV costs across carbon pricing and management mechanisms**

632 For details on acronyms, please refer to Table S 1. The costs presented are averages of sometimes very wide ranges, most often obtained from company  
633 surveys or calculations by the regulator in the impact assessment of its regulation. See <sup>(1)</sup> for details.

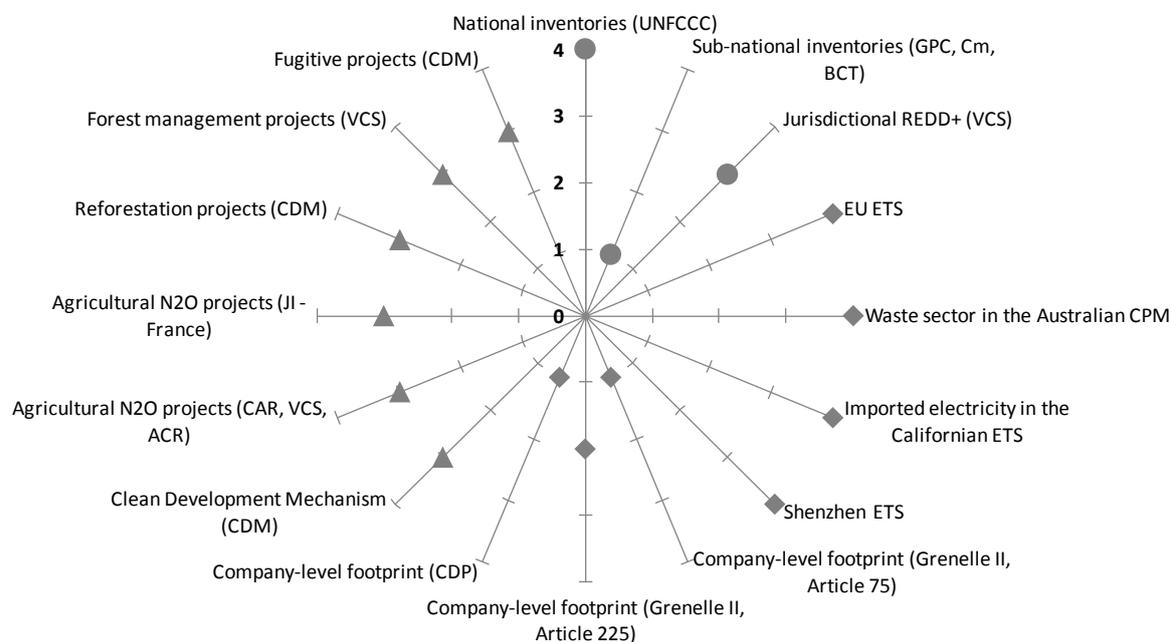
MRV scale		Standard or regulation	Cost per entity (€ yr <sup>-1</sup> )	Cost per emission (€ tCO <sub>2</sub> e <sup>-1</sup> )	Share of verification in total MRV costs	Original sources See for <sup>(1)</sup> details on the methods for each carbon pricing mechanism.
Jurisdiction	National inventories	United Nations Framework Convention on Climate Change (UNFCCC)	800,000	0.02	22%	1,28–30
	Sub-national inventories	Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC) / Covenant of mayors (Cm) / Bilan Carbone Territorial (BCT)	18,500	0.003	0%	31
	Jurisdictional REDD+	Verified Carbon Standard (VCS)	145,000	0.40	24%	32–40
Site/company	EU ETS	Monitoring and Reporting Regulation (MRR), Verification Regulation (VR)	22,000	0.07	40%	25,26,41–47
	Landfills in the Australian CPM	National Greenhouse and Energy Reporting Act (NGER)	4,862 (M&R only)	0.22	64%	48–50
	Imported electricity in the Californian ETS	Mandatory reporting of greenhouse gas emissions regulation (MRR)	73,000	0.14	not available	51–54
	Shenzhen ETS	Specification with guidance for quantification and reporting of the organization's greenhouse gas emissions (SZDB/Z 69)	no data	no data	no data	
	Company-level footprint	French Grenelle II law Article 75 / French Grenelle II law – Article 225 / Carbon Disclosure Project (CDP)	77,000 <sup>f</sup>	no data	no data	55
UNFCCC project	Projects	Clean Development Mechanism (CDM)	55,000	0.57	32%	32,34,36,37,39,56,57

<sup>f</sup> Includes the costs of all MRV frameworks used by the surveyed UK quoted companies which in some cases report under the CDP, the EU ETS and the CRC at the same time.

MRV scale		Standard or regulation	Cost per entity (€ yr <sup>-1</sup> )	Cost per emission (€ tCO <sub>2</sub> e <sup>-1</sup> )	Share of verification in total MRV costs	Original sources See for <sup>(1)</sup> details on the methods for each carbon pricing mechanism.
	Agricultural N <sub>2</sub> O projects	Climate Action Reserve (CAR) / VCS / American Carbon Registry (ACR) / Joint Implementation (JI) - France	no data	no data	no data	
	Reforestation projects	CDM	17,000	0.80	48%	<sup>33,58-62</sup>
	Forest management projects	VCS	Likely similar to CDM reforestation projects	Likely similar to CDM reforestation projects	Likely similar to CDM reforestation projects	
	Fugitive projects	CDM	167,000	0.22	15%	<sup>1</sup>

## 12. Figures

**Figure 1. Typology of verification requirements across carbon pricing and management mechanisms (CPMs)**



### Type of verification requirements

- 1 No verification requirements
- 2 Focused on reporting procedures rather than reported figures
- 3 Variable frequency, accredited third party
- 4 Annual frequency, accredited third party

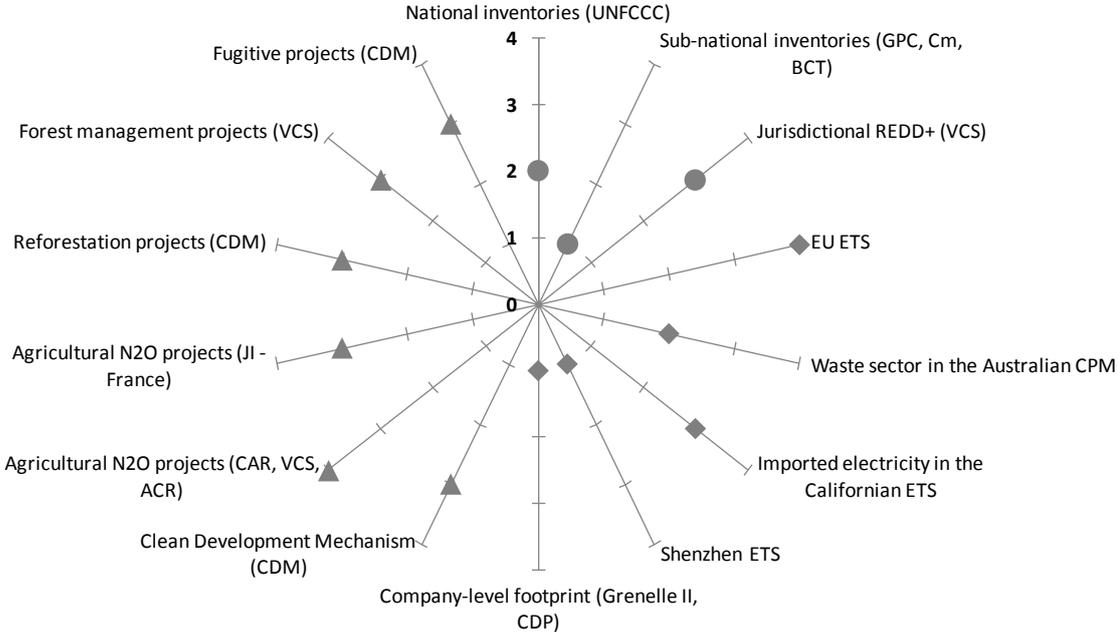
### Scale of the CPM

- Jurisdictional scale
- ◆ Site/company scale
- ▲ Offset project scale

For a detailed justification of the typology, see Table S1.

Sources: United Nations Framework Convention on Climate Change (UNFCCC)<sup>63</sup>, Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC)<sup>64</sup>, Covenant of mayors (Cm)<sup>65</sup>, Bilan Carbone Territorial (BCT)<sup>66</sup>, Verified Carbon Standard (VCS)<sup>67</sup>, Verification Regulation (VR)<sup>68</sup>, National Greenhouse and Energy Reporting Act (NGER)<sup>69</sup>, Mandatory reporting of greenhouse gas emissions regulation (MRR)<sup>15</sup>, Specification with guidance for quantification and reporting of the organization's greenhouse gas emissions (SZDB/Z 69)<sup>70</sup>, French Grenelle II law Article 75<sup>71,72</sup>, French Grenelle II law – Article 225<sup>71</sup>, Carbon Disclosure Project (CDP)<sup>73</sup>, Clean Development Mechanism (CDM)<sup>74</sup>, Climate Action Reserve (CAR)<sup>75</sup>, VCS<sup>76</sup>, American Carbon Registry (ACR)<sup>77</sup>, Joint Implementation (JI) - France<sup>78</sup>, CDM<sup>74</sup>, VCS<sup>76</sup>, CDM<sup>74</sup>.

**Figure 2. Typology of uncertainty requirements across carbon pricing and management mechanisms (CPMs)**



**Type of uncertainty requirements**

- 1 No uncertainty requirements**
- 2 Qualitative** (e.g. key categories should use a country-specific emission factor)
- 3 Quantitative, covering a few sources** of uncertainty (e.g. sampling error shall be no greater than 10%)
- 4 Quantitative, covering most sources** of uncertainty (e.g. total uncertainty shall be no greater than 2.5-10%)

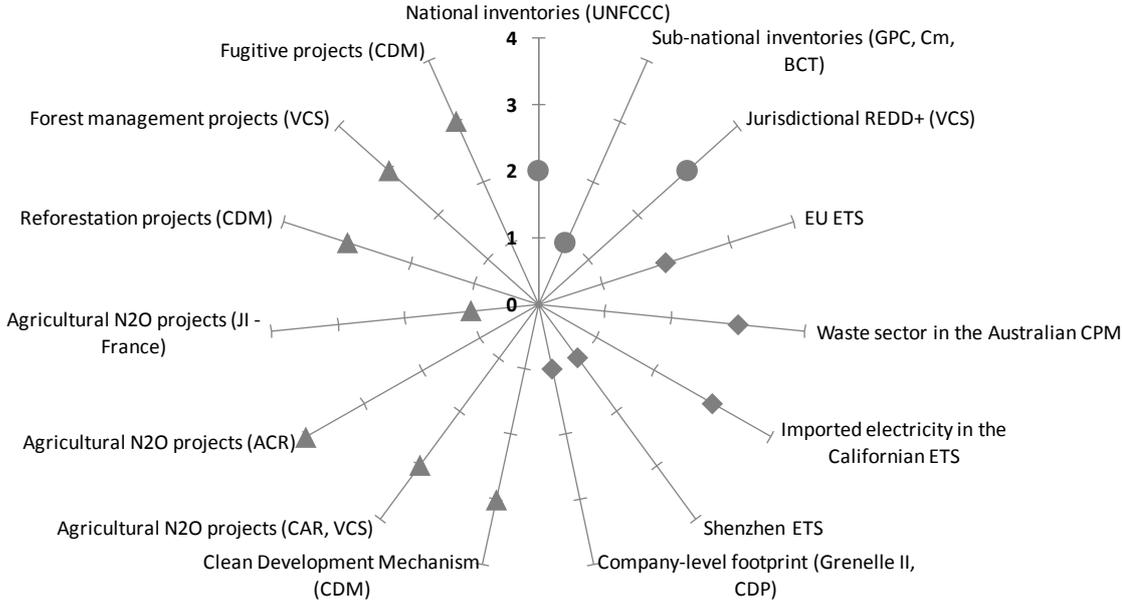
**Scale of the CPM**

- Jurisdictional scale
- ◆ Site/company scale
- ▲ Offset project scale

For a detailed justification of the typology, see Table S2.

Sources: UNFCCC<sup>6</sup>, GPC<sup>64</sup>, Cm<sup>65</sup>, BCT<sup>66</sup>, VCS<sup>79</sup>, Monitoring and Reporting Regulation (MRR)<sup>10</sup>, NGER<sup>69</sup>, MRR<sup>15</sup>, SZDB/Z 69<sup>70</sup>, CDP<sup>73</sup>, Grenelle II Article 225 & 75<sup>71,72</sup>, CDM<sup>11,80</sup>, CAR<sup>81</sup>, VCS<sup>82</sup>, ACR<sup>83</sup>, JI - France<sup>84</sup>, CDM<sup>85,86</sup>, VCS<sup>18,87</sup>, CDM<sup>19</sup>.

**Figure 3. Typology of incentives to reduce uncertainty across carbon pricing and management mechanisms (CPMs)**



**Type of incentive to reduce uncertainty**

- 1 None.**
- 2 Qualitative** (e.g. general principle of "continuous improvement").
- 3 Indirect** (e.g. through a conservative emission factor) **and quantitative, but covering only a few sources** of uncertainty.
- 4 Direct** (e.g. deduction factor) **and quantitative, covering most sources** of uncertainty.

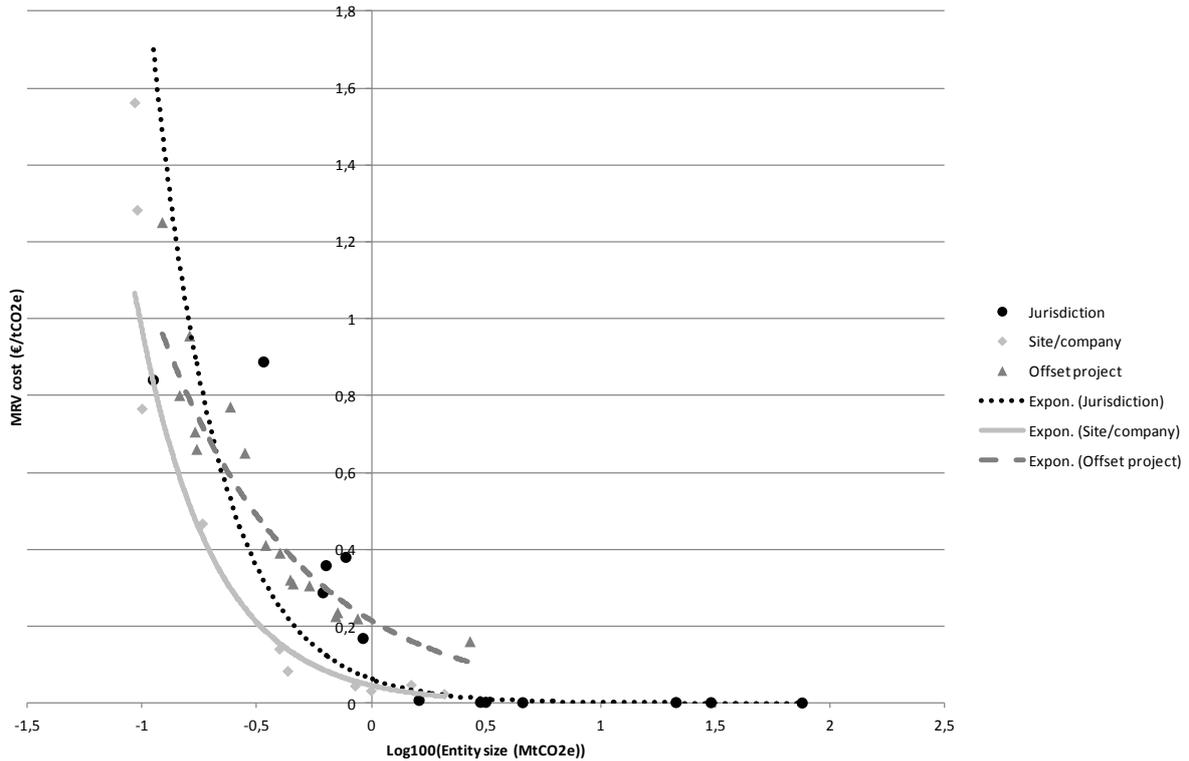
**Scale of the CPM**

- Jurisdictional scale
- ◆ Site/company scale
- ▲ Offset project scale

For a detailed justification of the typology, see Table S3.

Sources: UNFCCC<sup>6</sup>, GPC<sup>64</sup>, Cm<sup>65</sup>, BCT<sup>66</sup>, VCS<sup>79</sup>, MRR<sup>10</sup>, NGER<sup>69</sup>, MRR<sup>15</sup>, SZDB/Z 69<sup>70</sup>, CDP<sup>73</sup>, Grenelle II Article 225 & 75<sup>71,72</sup>, CDM<sup>80</sup>, CAR<sup>81</sup>, VCS<sup>82</sup>, ACR<sup>83</sup>, JI - France<sup>84</sup>, CDM<sup>85,86</sup>, VCS<sup>18,87</sup>, CDM<sup>19</sup>.

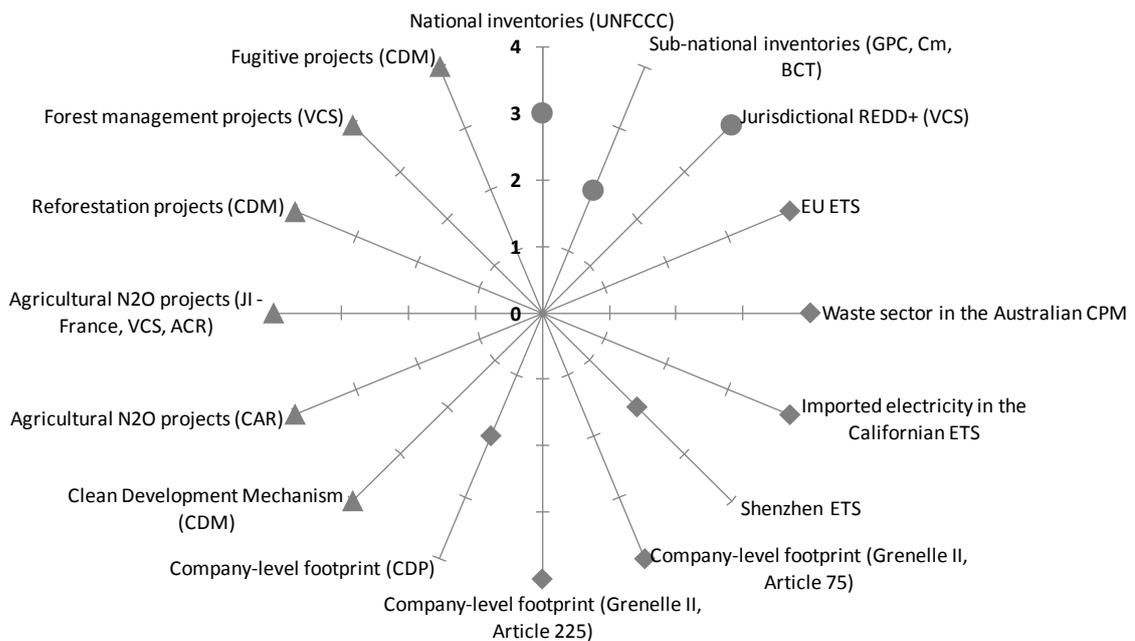
**Figure 4. Economies of scale in MRV**



Note: Each point corresponds to one of the (cost, size) pairs retained in <sup>(1)</sup>. It can be either an average for a give size range (e.g. EU ETS, CDM), or the estimated value for a specific entity (e.g. Germany’s national GHG inventory, a specific jurisdictional REDD project, ...). As a result, all points do not have the same representativeness. The full list of pairs is provided in Table S5.

Sources: see Table 1 and <sup>(1)</sup>.

**Figure 5. Typology of materiality provisions across carbon pricing and management mechanisms (CPMs)**



### Type of materiality provisions

- 1** More stringent requirements for smaller sources
- 2** No rules to adapt requirements stringency
- 3** Qualitative rules
- 4** Quantitative thresholds reducing stringency for smaller sources

### Scale of the CPM

- Jurisdictional scale
- ◆ Site/company scale
- ▲ Offset project scale

For a detailed justification of the typology, see Table S4.

Sources: UNFCCC<sup>6</sup>, GPC<sup>64</sup>, Cm<sup>65</sup>, BCT<sup>66</sup>, VCS<sup>67,79</sup>, MRR<sup>10</sup>, NGER<sup>69</sup>, MRR<sup>15</sup>, SZDB/Z 69<sup>70</sup>, Grenelle II Article 75<sup>71</sup>, Grenelle II – Article 225<sup>71</sup>, CDP<sup>73</sup>, CDM<sup>80</sup>, CAR<sup>81</sup>, ACR<sup>77</sup>, VCS<sup>76</sup>, JI<sup>78</sup>, CDM<sup>74,85,86</sup>, VCS<sup>18,76,87</sup>, CDM<sup>19</sup>.

### 13. Supplementary online materials

#### 13.1. Forty one systematic questions asked for each of the scheme reviewed

N.B.: The detailed answers to each of these questions for each of the schemes reviewed is available in <sup>(1)</sup>.

Context	
Regulator	The regulator is the entity which sets the MRV rules and/or guidelines. In most cases, the entity also sets the rules of the system in general. There can be several regulators for the same system (eg. UNFCCC COP and IPCC for national greenhouse gas inventories).
Type and level of incentive to comply	The type and severity of the punishments when non-compliance is detected (eg. inability to use the Kyoto flexibility mechanisms for national greenhouse inventories).
Entities concerned	Type of entity, number of entities, related market value
Sectors concerned	
Gases concerned	
Overall MRV costs	
Monitoring	
Rules	References of the official documents setting the monitoring rules for the system.
Other reference documents	Document references (i.e. ISO, GHG protocol, etc?)
Uncertainty requirements	Precision of monitoring required under the system, if applicable, expressed in % or tCO <sub>2</sub> e. In most cases, it will be a range of values varying with sectors, gases or categories.
Achieved uncertainty range	Precision of monitoring achieved under the system, if applicable, expressed in % or tCO <sub>2</sub> e. In most cases, it will be a range of values varying with sectors, gases or categories.
Cost range	Estimate of current costs of monitoring, expressed in € / country or site or company or project or tCO <sub>2</sub> e. The precise elements included in this cost estimate are provided on a case by case basis.
Scope	Scope of the emissions monitored. Three elements are specified:  A. Scope 1, 2 or 3 according to the definition of the GHG protocol (1 = direct emissions, 2 = direct emissions and emissions related to

	<p>electricity consumption, 3 = direct and indirect emissions).</p> <p>B. Territorial/jurisdictional vs patrimonial/operational (territorial emissions are the emissions occurring on the territory of a given jurisdiction, no matter who is responsible for these emissions (eg. emissions of an administrative region), whereas operational emissions corresponds to the emissions of the entity itself (eg. buildings, staff and activities of a regional council).</p> <p>C. Site vs entity: are the emissions from a type of site monitored or rather emissions from a type of entity?</p>
Frequency	Frequency of monitoring (daily, monthly, yearly, ...).
Source for activity data	What are the primary sources of information for activity data?
Uncertainty range for activity data	Precision of monitoring required under the system, if applicable, expressed in % or tCO <sub>2</sub> e. In most cases, it will be a range of values varying with sectors, gases or categories.
Source for emission factors	What are the primary sources of information for activity data?
Uncertainty range for emission factors	Precision of monitoring required under the system, if applicable, expressed in % or tCO <sub>2</sub> e. In most cases, it will be a range of values varying with sectors, gases or categories.
Direct measurement	Direct measurement is the measurement of the gas itself with a sensor (often optical), possibly integrated in an intelligent data assimilation system. Is direct measurement allowed or mandatory in the system? Under what conditions? Is it used or not used in practice?
Incentives to reduce uncertainty	Is there an incentive to improve monitoring precision built in the rules (eg. a conservativeness principle increasing carbon debits in proportion to monitoring uncertainty)?
Is requirements stringency adapted to the amount of emissions at stake (materiality)?	It makes good economic sense to be most stringent on the largest and most concentrated sources of emissions as the cost of monitoring tends to decrease with the concentration of emissions (economies of scale). Is this reflected in the rules/guidelines (eg. decreasing precision demand with decreasing installation size)?
<b>Reporting</b>	
Rules	References of the official documents setting the reporting rules for the system.
Other reference documents	Document references (i.e. ISO, GHG protocol, etc?)

Format	Description of the common reporting format if relevant.
Level of source disaggregation	Quantitative explanation (number of sites, production units, spatial resolution/aggregation, ...). There may be a difference between the required reporting level of disaggregation and the published level of aggregation.
Frequency	
Timeline	Key dates with regards reporting (eg. reporting deadline for year XX).
Language	Possible languages for reporting.
Is requirements stringency adapted to the amount of emissions at stake (materiality)?	It may make good economic sense to be most stringent on the largest and most concentrated sources of emissions as the cost of reporting tends to decrease with the concentration of emissions (economies of scale). Is this reflected in the rules/guidelines (eg. decreasing reporting frequency with decreasing installation size)?
Cost range	Estimate of current costs of reporting, expressed in € / country or site or company or project or tCO <sub>2</sub> e. The precise elements included in this cost estimate are provided on a case by case basis.
<b>Verification</b>	
Rules	References of the official documents setting the verification rules for the system.
Other reference documents	Document references
Format	Description of the common verification format if relevant.
Frequency	
Timeline	Key dates with regards verification (eg. verification deadline for year XX).
Language	Possible languages for verification.
Accredited entities for verification	Description of the procedure and key criteria for obtaining accreditation (if relevant). Examples of accredited entities.
Control of accredited entities	Description of the procedure and key criteria for maintaining accreditation (if relevant). Examples of reason for suspension (if relevant).
Cost of accreditation	Cost estimates of obtaining and maintaining the accreditation (€ per year).
Support of accredited entities	Description of the type of support that accredited entities receive, and from whom they receive it (if

	relevant).
Is requirements stringency adapted to the amount of emissions at stake (materiality)?	It may make good economic sense to be most stringent on the largest and most concentrated sources of emissions as the cost of verification tends to decrease with the concentration of emissions (economies of scale). Is this reflected in the rules/guidelines (eg. materiality/de minimis rules)?
Cost range	Estimate of current costs of verification, expressed in € / country or site or company or project or tCO <sub>2</sub> e. The precise elements included in this cost estimate are provided on a case by case basis.

## 13.2. Tables

**Table S 1. Verification requirements across carbon pricing mechanisms and management schemes**

Legend for the column “type of verification requirements”

	No verification requirements		Focused on reporting procedures rather than reported figures		Variable frequency, accredited third party		Annual frequency, accredited third party
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		Standard or regulation	Type of requirements	Verification requirements	
Jurisdiction	National inventories	United Nations Framework Convention on Climate Change (UNFCCC) <sup>2</sup>		Annual, performed by a team of UNFCCC accredited experts with the support of the UNFCCC Secretariat.	
	Sub-national inventories	Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC) <sup>3</sup> / Covenant of mayors (Cm) <sup>4</sup> / Bilan Carbone Territorial (BCT) <sup>5</sup>		None. However strongly recommended by all reporting guidelines and protocols.	
	Jurisdictional REDD+	Verified Carbon Standard (VCS) <sup>6</sup>		Variable frequency, performed by a UNFCCC or ISO accredited firm.	
Site/company	EU ETS	Verification Regulation (VR) <sup>7</sup>		Annual, performed by a firm accredited by the relevant national authority.	
	Waste sector in the Australian CPM	National Greenhouse and Energy Reporting Act (NGER) <sup>8</sup>		Annual for large emitters, performed by a team of experts accredited by the national authority. Variable for others (sample-based, paid by the regulator)	
	Imported electricity in the Californian ETS	Mandatory reporting of greenhouse gas emissions regulation (MRR) <sup>9</sup>		All electricity importers must be annually verified no matter their size. However, in-depth verifications are only conducted once per compliance period (a few of years), unless a specific risk is identified.	
	Shenzhen ETS	Specification with guidance for quantification and reporting of the organization's greenhouse gas emissions (SZDB/Z 69) <sup>10</sup>		Annual, performed by a firm accredited by the relevant authority (DRC).	
	Company-level footprint	French Grenelle II law Article 75 <sup>11,12</sup>			None.
		French Grenelle II law – Article 225 <sup>11</sup>			Annual. Limited to completeness of information and "fairness". No detailed set of guidelines to verify the reports against.
		Carbon Disclosure Project (CDP) <sup>13</sup>			None. 67% of companies voluntarily have their footprint verified, but even then the verification tends to be limited to "internal consistency". Verification increases the company's overall transparency score.
Offset project	Projects	Clean Development Mechanism (CDM) <sup>14</sup>		Variable frequency, performed by a UNFCCC accredited firm.	
	Agricultural N2O projects	Climate Action Reserve (CAR) <sup>15</sup> / VCS <sup>16</sup> / American Carbon Registry (ACR) <sup>17</sup>		Variable frequency, performed by a UNFCCC or ISO accredited firm.	
		Joint Implementation (JI) - France <sup>18</sup>			Variable frequency, performed by a UNFCCC or EU ETS accredited firm.

Reforestation projects	CDM <sup>14</sup>		Variable frequency, performed by a UNFCCC accredited firm.
Forest management projects	VCS <sup>16</sup>		Variable frequency, performed by a UNFCCC or ISO accredited firm.
Fugitive projects	CDM <sup>14</sup>		Variable frequency, performed by a UNFCCC accredited firm.

**Table S 2. Type of uncertainty requirements across carbon pricing mechanisms and management schemes**

Legend for the column “type of uncertainty requirements”

	None		<b>Qualitative</b> (e.g. key categories should use a country-specific emission factor)		<b>Quantitative, covering a few sources</b> of uncertainty (e.g. sampling error shall be no greater than 10%)		<b>Quantitative, covering most sources</b> of uncertainty (e.g. total uncertainty shall be no greater than 2.5-10%)
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For details on acronyms, please refer to Table S 1.

		Standard regulation or	Type of requirements	Formal Requirements
<b>Jurisdiction</b>	National inventories	UNFCCC <sup>19</sup>		Key categories must use at least Tier 2. General objective to reduce uncertainty over the long run.
	Sub-national inventories	GPC <sup>3</sup> / Cm <sup>4</sup> / BCT <sup>5</sup>		None.
	Jurisdictional REDD+	VCS <sup>20</sup>		Accuracy of land classification must be at least 75%. If activity-based accounting (only baseline is monitored at jurisdictional level), a deduction is applied if the uncertainty of emissions factor exceeds 30%. If land-based accounting (full jurisdictional MRV), a deduction is applied if the total uncertainty of baseline emissions exceeds 50%. IPCC default emission factors (Tier 1) can only be used for sources representing less than 15% of total carbon stocks.
<b>Site/company</b>	EU ETS	Monitoring and Reporting Regulation (MRR) <sup>21</sup>		Uncertainty on activity data must be below 1.5-15%, depending on the size of the emission source. Uncertainty requirements on emission factors may be qualitative (e.g. mandatory use of a given value) or quantitative (e.g. 1% for the carbon content of fuels, minimum frequency for fuel sampling). Overall uncertainty must be below 2.5-10% if a direct measurement approach is used.
	Waste sector in the Australian CPM	NGER <sup>8</sup>		No explicit requirements beyond a qualitative objective to minimize uncertainty. However, the relevant Australian or international measurement standards must be applied when facility-specific emission factors are used.
	Imported electricity in the Californian ETS	MRR <sup>9</sup>		Overall uncertainty of electricity meters at facility level must be lower than 5%. Otherwise, no requirements on the source of emissions itself beyond the proof of origin (NERC e-tag) and the requirements applied in the jurisdiction where electricity is produced (e.g. US EPA GHG Reporting Rule).
	Shenzhen ETS	SZDB/Z 69 <sup>10</sup>		None yet specified. In addition, the use of default factors is always allowed, and therefore likely to be largely used since it is cheaper both per se and because it fits well with the existing reporting on energy use.
	Company-level footprint	CDP <sup>13</sup> /Grenelle II Article 225 & 75 <sup>11,12</sup>		None.
<b>Offset project</b>	Projects	CDM <sup>22,23</sup>		No explicit requirement in the overarching guidelines except for sampling and survey for which uncertainty must be below 10%. Sub-sector specific calculation tools and methodologies may introduce either qualitative - through the mandatory use of a given method or meter - or quantitative requirements but none is systematic.
	Agricultural projects	N <sub>2</sub> O		A deduction is applied if the uncertainty associated with the emission factor exceeds 15%. For activity data, projects rely on data reported and verified under other existing regulations which set their own requirements (e.g. federal or state BMP programs).
				For activity data, projects rely on data reported and verified under the Common agricultural policy which sets its own requirements.

		Standard regulation	or	Type of requirements	Formal Requirements
	Reforestation projects	CDM <sup>28,29</sup>			Depends on methodologies: either a fixed 10% maximum or a deduction based on the sampling error on tree biomass.
	Forest management projects	VCS <sup>30,31</sup>			In some methodologies, the overall uncertainty - including model errors such as allometry - is considered in the deduction factor. In others, the approach is similar to reforestation projects under the CDM and limited to sampling error.
	Fugitive projects	CDM <sup>32</sup>			If gas flow rate is measured (approach 2), a deduction is applied based on the uncertainty of gas flow rate measurement.

**Table S 3. Incentives to reduce monitoring uncertainty across carbon pricing mechanisms and management schemes**

Legend for the column “type of incentive to reduce uncertainty”

None			<b>Qualitative</b> (e.g. general principle of "continuous improvement")		<b>Indirect</b> (e.g. through a conservative emission factor) <b>and quantitative, but covering only a few sources</b> of uncertainty.		<b>Direct</b> (e.g. deduction factor) <b>and quantitative, covering most sources</b> of uncertainty.
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For details on acronyms, please refer to Table S 1.

		Standard regulation	or	Type of incentive	Requirements
Jurisdiction	National inventories	UNFCCC <sup>19</sup>			Key categories must use at least Tier 2. General objective to reduce uncertainty over the long run.
	Sub-national inventories	GPC <sup>3</sup> / Cm <sup>4</sup> / BCT <sup>5</sup>			None.
	Jurisdictional REDD+	VCS <sup>20</sup>			"If activity-based accounting (only baseline is monitored at jurisdictional level), a deduction is applied if the uncertainty of emissions factor exceeds 30%. If land-based accounting (full jurisdictional MRV), a deduction is applied if the total uncertainty of baseline emissions exceeds 50%. IPCC default emission factors (Tier 1) can only be used for sources representing less than 15% of total carbon stocks.
Site/company	EU ETS	MRR <sup>21</sup>			None once the mandatory threshold is met. A principle of "continuous improvement" is nevertheless embedded in the MRR.
	Waste sector in the Australian CPM	NGER <sup>8</sup>			Incentive to upgrade to method 2 when methane capture is higher than 75%.
	Imported electricity in the Californian ETS	MRR <sup>9</sup>			None, unless the source is cleaner than the emission factor for unspecified sources, in which case there is an incentive to upgrade to "specified source". Inversely, there is an incentive to maintain a high uncertainty "unspecified" status if the source is dirtier than the default emission factor.
	Shenzhen ETS	SZDB/Z 69 <sup>10</sup>			None yet specified. To the contrary, the use of uncertain default factors is always allowed, and therefore likely to be largely used since it is cheaper both per se and because it fits well with the existing reporting on energy use.

		Standard or regulation	Type of incentive	Requirements
	Company-level footprint	CDP <sup>13</sup> /Grenelle II Article 225 & 75 <sup>11,12</sup>		None.
Offset project	Projects	CDM <sup>23</sup>		None in the overarching guidelines except for sampling and surveys for which the more conservative uncertainty bound must be used. Sub-sector specific methodologies may introduce either explicit - deduction proportional to uncertainty - or implicit - choice between a conservative default value and a more precise and more costly monitoring method - but none is systematic.
	Agricultural projects N <sub>2</sub> O	CAR <sup>24</sup> / VCS <sup>25</sup>		A deduction is applied if the uncertainty associated with the emission factor exceeds 15%.
		ACR <sup>26</sup>		A deduction is applied if the uncertainty associated with the emission factor exceeds 15%. Project proponent is allowed to come up with a project-specific emission factor. The conservative default emission factor provides an incentive to do so.
		JI - France <sup>27</sup>		None.
	Reforestation projects	CDM <sup>28,29</sup>		In some methodologies, a deduction is applied based on the sampling error on tree biomass.
	Forest management projects	VCS <sup>30,31</sup>		In one methodology, the overall uncertainty - including model errors such as allometry - is considered in the deduction factor. In the others, the deduction is applied only based on sampling error.
Fugitive projects	CDM <sup>32</sup>		If gas flow rate is measured (approach 2), a deduction is applied based on the uncertainty of gas flow rate measurement.	

**Table S 4. “Materiality” across carbon pricing mechanisms and management schemes**

Legend for the column “type of materiality provisions”

	More stringent requirements for smaller sources		No rules to adapt requirements stringency		Qualitative rules		Quantitative thresholds reducing stringency for smaller sources
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For details on acronyms, please refer to Table S 1.

	Standard or regulation		Rules to adapt requirements stringency to the amount of emissions at stake
<b>Jurisdiction</b>	National inventories	UNFCCC <sup>19</sup>	None beyond the key category analysis <sup>7</sup> .
	Sub-national inventories	GPC <sup>3</sup> / Cm <sup>4</sup> / BCT <sup>5</sup>	None.
	Jurisdictional REDD+	VCS <sup>6,20</sup>	Pools which are not expected to become sources compared to the baseline need not be accounted. Small source can be considered de minimis up to an overall 10% of emissions. Frequency of reporting and verification is flexible up to the minimum five year return. Materiality between 1% (large projects) and 5% (small projects) during verification.
<b>Site/company</b>	EU ETS	MRR <sup>21</sup>	Inclusion threshold based on various criteria (e.g. thermal input > 20 MW) which can be quite low in terms of emissions (64% of installations below 25 ktCO <sub>2</sub> e/yr and 30% below 5 ktCO <sub>2</sub> e/yr). Simplified requirements for installations below 25 ktCO <sub>2</sub> e/yr. Possibility to reduce stringency based on a cost/benefit analysis where benefit is a function of the amount of emissions at stake. Materiality between 2% (large installations) and 5% (small installations) during verification. Frequency of improvement report depends on installation size.
	Waste sector in the Australian CPM	NGER <sup>8</sup>	Inclusion threshold of 25 ktCO <sub>2</sub> e/yr (or 10 ktCO <sub>2</sub> e/yr in the vicinity of an already included landfill). Verification is only systematic for facilities above 125 ktCO <sub>2</sub> e/yr. Smaller installations are verified on an arbitrary basis, to the expense of the regulator.
	Imported electricity in the Californian ETS	MRR <sup>9</sup>	No inclusion threshold for electricity importers: all have to report and verify their emissions, no matter how small they are. Materiality set at 5% of facility-level emissions during verification.
	Shenzhen ETS	SZDB/Z 69 <sup>10</sup>	None.
	Company-level footprint	Grenelle II Article 75 <sup>11</sup>	Inclusion thresholds (e.g. private companies with more than 500 employees).
		Grenelle II – Article 225 <sup>11</sup>	Inclusion thresholds (e.g. private companies with more than 500 employees and an annual income or assets worth more than € 100 million).
	CDP <sup>13</sup>	None.	
<b>Offset project</b>	Projects	CDM <sup>23</sup>	Reporting and verification frequency is up to the project developer. A minimal monitoring frequency is imposed based reporting frequency. A higher monitoring frequency is therefore mandatory for larger projects which tend to opt for a high reporting frequency. Simplified requirements for small-scale and micro-scale projects. Materiality threshold during verification more gradual than EU ETS: from 10% (<20 ktCO <sub>2</sub> e/yr) to 0.5% (> 500 ktCO <sub>2</sub> e/yr).

<sup>7</sup> A materiality provision has recently been inserted in the revised reporting guidelines which will be implemented in 2015. Sources simultaneously below 0.05% of the national total and below 500 ktCO<sub>2</sub>e need not be estimated (decision 15/CP.17). Materiality is still absent from the verification of national GHG inventories.

Standard or regulation		Rules to adapt requirements stringency to the amount of emissions at stake
Agricultural N <sub>2</sub> O projects	CAR <sup>24</sup>	For monitoring, it is the contrary: an uncertainty adjustment factor makes requirements more stringent for projects with fewer fields. Reporting must be done yearly or every two years for single-field projects. For site visit, it is the contrary: the percentage of fields that must be visited by the auditor is inversely proportional to project size. Materiality threshold of 5% during verification.
	ACR <sup>17</sup> / VCS <sup>16</sup> / JI <sup>18</sup>	Reporting and Verification frequency is up to the project developer. Materiality threshold between 1% and 5% for VCS during verification.
Reforestation projects	CDM <sup>14,28,29</sup>	Emissions from forestry operations are considered de minimis. Pools which are not a source need not be accounted (in practice, only living biomass is accounted). MRV frequency is up to the project proponent. Materiality threshold between 0.5% and 10% during verification.
Forest management projects	VCS <sup>16,30,31</sup>	Depending on the methodology, several sources may be considered de minimis (forestry operations, CH <sub>4</sub> and N <sub>2</sub> O emissions from biomass burning). Depending on the methodology, some pools need not be accounted. In any case, pools which are not a source need not be accounted. MRV frequency is up to the project proponent. Materiality threshold between 1% and 5% during verification.
Fugitive projects	CDM <sup>32</sup>	No specific rules beyond what applies to all CDM projects (see above).

**Table S 5. List of pairs for figure 5**

		Standard or regulation	Case study / project type	MRV cost (€/tCO <sub>2</sub> e)	Entity size (MtCO <sub>2</sub> e)
Jurisdiction	National inventories	UNFCCC	USA (Pacala et al., 2010, Bellassen and Stephan upcoming)	0,000155513	5787,284
	National inventories	UNFCCC	Italy (Pacala et al., 2010, Bellassen and Stephan upcoming)	0,001418588	458,202
	National inventories	UNFCCC	Germany (Pacala et al., 2010, Bellassen and Stephan upcoming)	0,001026106	925,83
	Sub-national inventories	GHG Protocol / Covenant of mayors / Bilan Carbone Territorial	Dunkerque Grand Littoral (ABC 2013, Bellassen and Stephan upcoming)	0,001	21
	Sub-national inventories	GHG Protocol / Covenant of mayors / Bilan Carbone Territorial	Lille Metropole (ABC 2013, Bellassen and Stephan upcoming)	0,002	10
	Sub-national inventories	GHG Protocol / Covenant of mayors / Bilan Carbone Territorial	Marseille Provence Métropole (ABC 2013, Bellassen and Stephan upcoming)	0,002	9
	Sub-national inventories	GHG Protocol / Covenant of mayors / Bilan Carbone Territorial	Grand Chalon (ABC 2013, Bellassen and Stephan upcoming)	0,007	2,615
	Sub-national inventories	GHG Protocol / Covenant of mayors / Bilan Carbone Territorial	Communauté de communes de la Vallée de Chamonix-Mont-Blanc (ABC 2013, Bellassen and Stephan upcoming)	0,84	0,0125
	Jurisdictional REDD+	VCS	TBNP (Rendon et al. 2013, Bellassen and Stephan upcoming)	0,36	0,40
	Jurisdictional REDD+	VCS	SFM-MC (Rendon et al. 2013, Bellassen and Stephan upcoming)	0,17	0,85
	Jurisdictional REDD+	VCS	Noel Kempf (Rendon et al. 2013, Bellassen and Stephan upcoming)	0,89	0,11
Jurisdictional REDD+	VCS	Juma (Rendon et al. 2013, Bellassen and Stephan upcoming)	0,29	0,38	
Jurisdictional REDD+	VCS	South East Asia, (Pearson et al. 2013, Bellassen and Stephan upcoming)	0,38	0,60	
Site/company	EU ETS	MRR	Installations < 25 ktCO <sub>2</sub> e yr-1, Aether (2010)	1,28	0,01
	EU ETS	MRR	Installations between 25 and 50 ktCO <sub>2</sub> e yr-1, Aether (2010)	0,47	0,03
	EU ETS	MRR	Installations between 50 and 500 ktCO <sub>2</sub> e yr-1, Aether (2010)	0,14	0,16
	EU ETS	MRR	Installations > 500 ktCO <sub>2</sub> e yr-1, Aether (2010)	0,05	2,24
	EU ETS	MRR	Installations > 1,4 MtCO <sub>2</sub> e yr-1, Jaraite et al (2010)	1,56	0,01
	EU ETS	MRR	Installations between 0,067 and 1,4 MtCO <sub>2</sub> e yr-1, Jaraite et al (2010)	0,04	0,73
	EU ETS	MRR	Installations < 67 ktCO <sub>2</sub> e yr-1, Jaraite et al (2010)	0,02	4,35
	EU ETS	MRR	Installations emitting 10 ktCO <sub>2</sub> e yr-1, Heindl (2012)	0,76	0,01
Offset project	Projects	CDM	Biomass energy, Warnecke (2013)	0,65	0,079
	Projects	CDM	Coal mine/bed methane, Warnecke (2013)	0,235	0,51
	Projects	CDM	EE households, Warnecke (2013)	0,955	0,026
	Projects	CDM	EE own generation, Warnecke (2013)	0,32	0,197
	Projects	CDM	Fossil fuel switch, Warnecke (2013)	0,225	0,491
	Projects	CDM	Hydro large-scale, Warnecke (2013)	0,31	0,208
	Projects	CDM	Hydro small-scale, Warnecke (2013)	0,705	0,029
	Projects	CDM	Landfill gas, Warnecke (2013)	0,39	0,16
	Projects	CDM	Methane avoidance, Warnecke (2013)	0,77	0,059
	Projects	CDM	N <sub>2</sub> O nitric acid, Warnecke (2013)	0,305	0,289
	Projects	CDM	N <sub>2</sub> O adipic acid, Warnecke (2013)	0,16	7,294
	Projects	CDM	Wind large-scale, Warnecke (2013)	0,41	0,12
	Projects	CDM	Wind small-scale, Warnecke (2013)	1,25	0,015
	Projects	CDM	Solar, Warnecke (2013)	0,66	0,03
	Projects	CDM	Fugitives, Bellassen and Stepan (upcoming)	0,219087126	0,762
	Projects	CDM	Reforestation, Bellassen and Stepan (upcoming)	0,8	0,02125

### 13.3. References

1. *Accounting for Carbon: Monitoring, Reporting and Verifying Emissions in the Climate Economy.* (Cambridge University Press, upcoming).
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