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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 topic¹. '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 Ascui and Lovell² 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. N₂O 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 CO₂ per liter of burnt fuel, tons of CO₂e 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 project³⁻⁵.

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 IPCC⁶: 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 Cochran³: *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 client⁷. 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 Protocol⁸ or IPCC⁶). 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 schemes⁹.

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 biased⁶.
202 The EU ETS limits the uncertainty of some elements but does not reward further uncertainty
203 reduction as long as the threshold is met¹⁰.

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 samples¹¹. 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 variables⁹. Yet, these incentives remain limited in the CDM for
209 three reasons¹²:

210 (1) in most cases, conservativeness only concerns one or two parameters whereas the number of
211 parameters involved in the calculation often exceeds ten¹³. 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. UNFCCC¹⁴);

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 plant¹⁵. 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 commerce¹⁶. The EU
231 faced a similar dilemma when setting an emission factor to oil produced from Canadian tar sands
232 under the Fuel Quality Directive¹⁷. In offset schemes however, the risk of adverse selection²⁰ 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 management¹⁸) or in proportion to the uncertainty of one component of the estimate (e.g.
239 leak flow rate in CDM AM0023 on fugitive emissions¹⁹).

240 These provisions may make sense in offset schemes which are vulnerable to adverse selection²⁰:
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 uncertainty²¹. 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 ETS²² 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 CO₂e* 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 tCO₂e (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 firms⁹. 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^{23,24}. 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 costs²⁵. 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 tCO₂e* basis²⁶. 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 total²⁵. 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 tCO₂e
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 EPA²⁶ assessed the effectiveness of a minimum threshold for inclusion in the
330 perimeter of the regulation. Compared to 25,000 tCO₂e yr⁻¹ threshold retained in the US, a 10,000
331 tCO₂e yr⁻¹ threshold would increase costs by 35% and cover only 1% more emissions. Conversely,
332 decreasing the inclusion threshold to 100,000 tCO₂e yr⁻¹ 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. Cochran³
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 recovery²⁷.

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 tCO₂e
400 per year are MRVed under the EU ETS while verification is only mandatory for sites emitting over
401 125,000 tCO₂e 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.

409 8. References

- 410 1. **Bellassen, V. & Stephan, N. (eds), *Accounting for Carbon: Monitoring, Reporting***
411 ***and Verifying Emissions in the Climate Economy*. (Cambridge University Press,**
412 **2015).**
- 413 2. Ascuri, F. & Lovell, H. As frames collide: making sense of carbon accounting.
414 *Accounting, Auditing & Accountability Journal* **24**, 978–999 (2011).
- 415 3. Cochran, I. *A Use-Based Analysis of Local-Scale GHG Inventories*. 37 p (CDC Climat
416 Research, 2010).
- 417 4. IGES. *Measurement, Reporting and Verification (MRV) for low carbon development:*
418 *Learning from experience in Asia*. 136 p (IGES, 2012).
- 419 5. Ninomiya, Y. *Classification of MRV of GHG Emissions/Reductions: for the*
420 *discussions on NAMAs and MRV*. 10 (IGES, 2012).
- 421 6. IPCC. *2006 IPCC guidelines for national greenhouse gas inventories*. (IGES, 2006).
- 422 7. Cormier, A. & Bellassen, V. The risks of CDM projects: How did only 30% of
423 expected credits come through? *Energy Policy* **54**, 173–183 (2013).
- 424 8. GHG Protocol. *GHG Protocol guidance on uncertainty assessment in GHG*
425 *inventories and calculating statistical parameter uncertainty*. 17 p (WRI/WBCSD,
426 2004).
- 427 9. **Warnecke, C. Can CDM monitoring requirements be reduced while maintaining**
428 **environmental integrity? *Climate Policy* 24 p (2014).**
- 429 10. European Commission. *Commission Regulation (EU) No 601/2012 of 21 June 2012*
430 *on the monitoring and reporting of greenhouse gas emissions pursuant to Directive*
431 *2003/87/EC of the European Parliament and of the Council*. (2012).
- 432 11. UNFCCC. *Standard for sampling and surveys for cdm project activities - version 3.0*.
433 8 p (2011).
- 434 12. **Shishlov, I. & Bellassen, V. Review of monitoring uncertainty requirements in the**
435 **CDM. 33 p (CDC Climat Research, 2014).**
- 436 13. Barker, A. & Robinson, R. *Uncertainty in Monitoring of Carbon Offsetting Projects*.
437 50 p (National Physical Laboratory, 2014).
- 438 14. UNFCCC. *Tool to calculate project or leakage CO2 emissions from fossil fuel*
439 *combustion*. 8 p (2008).
- 440 15. California Air Resource Board. *ARB Mandatory Reporting Regulation. California*
441 *Code of Regulations Title 17, CCR, sections 95100 - 95158*, (2013).
- 442 16. **Cosbey, A. et al. A Guide for the Concerned: Guidance on the elaboration and**
443 **implementation of border carbon adjustment. 24 p (Entwined, 2012).**
- 444 17. Kokoni, S. & Skea, J. Input–output and life-cycle emissions accounting: applications
445 in the real world. *Climate Policy* **14**, 372–396 (2014).

- 446 18. VCS. *VM0012 Improved Forest Management in Temperate and Boreal Forests*
447 *(LiPF) - Version 1.1*. 83 p (Verified Carbon Standard, 2012).
- 448 19. UNFCCC. *Approved baseline and monitoring methodology AM0023 - Leak detection*
449 *and repair in gas production, processing, transmission, storage and distribution*
450 *systems and in refinery facilities - Version 04.0.0*. 21 p (2011).
- 451 20. Millard-Ball, A. The trouble with voluntary emissions trading: Uncertainty and
452 adverse selection in sectoral crediting programs. *Journal of Environmental Economics*
453 *and Management* **65**, 40–55 (2013).
- 454 21. Shishlov, I. MRV incentives: theory and practice (the CDM experience). (2014).
- 455 22. European Commission. *Inclusion of additional activities and gases into the EU-*
456 *emissions trading scheme*. (European Commission, Directorate General for
457 Environment, 2006).
- 458 23. Bellassen, V. & Alberola, E. European Offset Projects: A tool to rally Poland towards
459 the 2030 Energy Climate Package. *Tendances Carbone 1* (2014).
- 460 24. Shishlov, I., Bellassen, V. & Leguet, B. *Joint Implementation: a frontier mechanism*
461 *within the borders of an emissions cap*. 40 p (CDC Climat Research, 2012).
- 462 25. King, K., Pye, S. & Davison, S. *Assessing the cost to UK operators of compliance*
463 *with the EU Emissions Trading System*. 31 p (Aether, 2010).
- 464 26. US EPA. *Regulatory Impact Analysis for the Mandatory Reporting of Greenhouse*
465 *Gas Emissions Final Rule (GHG Reporting)*. 213 p (United States Environmental
466 Protection Agency, 2009).
- 467 27. Stephan, N., Bellassen, V. & Alberola, E. *Use of Kyoto credits by European industrial*
468 *installations: from an efficient market to a burst bubble*. 24 p (CDC Climat Research,
469 2014).
- 470 28. **Hogan, P. et al. Tracking Emissions and Mitigation Actions: Current Practice in**
471 **China, Germany, Italy, and the United States. 78 p (Climate Policy Initiative,**
472 **2012).**
- 473 29. **Pacala, S. et al. Verifying Greenhouse Gas Emissions: Methods to Support**
474 **International Climate Agreements Committee on Methods for Estimating**
475 **Greenhouse Gas Emissions, National Research Council Report. National**
476 **Academy of Sciences, USA 110 p (2010).**
- 477 30. UNFCCC. *Programme budget for the biennium 2012–2013*. 10 p (2012).
- 478 31. ABC. *Synthèse Enquête Flash 2013*. (Association Bilan Carbone, 2013).
- 479 32. Beaurain, F. & Schmidt-Traub, G. *Developing CDM Programmes of Activities: a*
480 *Guidebook*. 75 p (South Pole Carbon Asset Management Ltd., 2010).
- 481 33. Chenost, C. & Gardette, Y-M. *Bringing forest carbon projects to the market*. (UNEP,
482 2010).
- 483 34. Guigon, P., Bellassen, V. & Ambrosi, P. *Voluntary Carbon Markets: What the*
484 *Standards Say...* 46 p (CDC Climat Research, 2009).
- 485 35. Hardcastle, P. D. & Baird, D. *Capability and cost assessment of the major forest*
486 *nations to measure and monitor their forest carbon*. (Office of Climate Change,
487 2008).

- 488 36. Krey, M. Transaction costs of unilateral CDM projects in India—results from an
489 empirical survey. *Energy Policy* **33**, 2385–2397 (2005).
- 490 37. Michaelowa, A. & Stronzik, M. *Transaction Costs of the Kyoto Mechanisms*. (2002).
- 491 38. Plugge, D., Baldauf, T. & Köhl, M. The global climate change mitigation strategy
492 REDD: monitoring costs and uncertainties jeopardize economic benefits. *Climatic*
493 *Change* **119**, 247–259 (2013).
- 494 39. UNEP. *Guidebook to Financing CDM Projects*. (2007).
- 495 40. Böttcher, H. *et al.* An assessment of monitoring requirements and costs of ‘Reduced
496 Emissions from Deforestation and Degradation’. *Carbon Balance and Management* **4**,
497 7 (2009).
- 498 41. AEA. *Costs of Compliance with the EU Emissions Trading Scheme*. (UK Environment
499 Agency, 2006).
- 500 42. ETG. *Administrative Cost of the Emissions Trading Scheme to Participants*. 2 p
501 (Emissions Trading Group, 2008).
- 502 43. European Commission. *Impact assessment - Accompanying the document*
503 *COMMISSION REGULATION (EU) No .../.. of XXX on the monitoring and reporting*
504 *of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European*
505 *Parliament and of the Council and COMMISSION REGULATION (EU) No .../.. of*
506 *XXX on the verification of greenhouse gas emission reports and tonne-kilometre*
507 *reports and the accreditation of verifiers pursuant to Directive 2003/87/EC of the*
508 *European Parliament and of the Council*. 56 p (2012).
- 509 44. European Commission. *Impact assessment - Accompanying document to the Proposal*
510 *for a directive of the European parliament and of the Council amending Directive*
511 *2003/87/EC so as to improve and extend the EU greenhouse gas emission allowance*
512 *trading system*. 255 p (2008).
- 513 45. Graus, W. & Voogt, M. *Small installations within the EU Emissions Trading Scheme*.
514 32 p (European Commission & Ecofys, 2007).
- 515 46. Jaraité, J., Convery, F. & Di Maria, C. Transaction costs for firms in the EU ETS:
516 lessons from Ireland. *Climate Policy* **10**, 190–215 (2010).
- 517 47. Heindl, P. *Transaction costs and tradable permits: Empirical evidence from the EU*
518 *emissions trading scheme*. (ZEW (Center for European Economic Research), 2012).
- 519 48. DIICCSRTE. *National Inventory Report 2011*. (Department of Industry, Innovation,
520 Climate Change, Science, Research and Tertiary Education, 2013).
- 521 49. House of Representatives. *National Greenhouse and Energy Reporting Bill,*
522 *Explanatory Memorandum*. (2007).
- 523 50. Ministry of Finance. *Australia’s plan for clean energy future*. (2011).
- 524 51. ARB. *Initial Statement of Reasons for Rulemaking, amendments to the regulation for*
525 *the mandatory reporting of greenhouse gas emissions*. (California Air Resource
526 Board, 2013).
- 527 52. ARB. *Initial Statement of Reasons for Rulemaking, amendments to the regulation for*
528 *the mandatory reporting of greenhouse gas emissions and conforming amendments to*
529 *the definition sections of the AB 32 cost of implementation fee regulation and the cap-*
530 *and-trade regulation*. (California Air Resource Board, 2012).

- 531 53. ARB. *Initial Statement of Reasons for Rulemaking, aproposed regulation for*
532 *mandatory reporting of greenhouse gas emissions pursuant to the Global warming*
533 *solutions act of 2006.* (California Air Resource Board, 2007).
- 534 54. ARB. *Initial Statement of Reasons for Rulemaking, revisions to the regulation for*
535 *mandatory reporting of greenhouse gas emissions pursuant to the Global warming*
536 *solutions act of 2006.* (California Air Resource Board, 2010).
- 537 55. Price Waterhouse Coopers & Carbon Disclosure Project. *Review of the Contribution*
538 *of Reporting to GHG Emissions Reductions and Associated Costs and Benefits.* 109 p
539 (UK Department for Environment, Food and Rural Affairs, 2007).
- 540 56. IGES. *One Hundred Questions & Answers about MRV in Developing Countries.*
541 (Institute for Global Environmental Strategies, 2013).
- 542 57. Warnecke, C., Klein, N., Perroy, R. & Tippman, R. *CDM Market Support Study.*
543 (KfW Bankengruppe, 2013).
- 544 58. Cacho, O. J., Wise, R. M. & MacDicken, K. G. Carbon Monitoring Costs and their
545 Effect on Incentives to Sequester Carbon through Forestry. *Mitigation and Adaptation*
546 *Strategies for Global Change* **9**, 273–293 (2004).
- 547 59. Martel, S. *Évaluation préliminaire des coûts de suivi pour un projet en métropole.*
548 (2013).
- 549 60. Pearson, T. R. H., Brown, S., Sohngen, B., Henman, J. & Ohrel, S. Transaction costs
550 for carbon sequestration projects in the tropical forest sector. *Mitigation and*
551 *Adaptation Strategies for Global Change* (2013).
- 552 61. Torres, D. *Les méthodes et coûts du suivi pratiqués dans les pays en développement.*
553 (2013).
- 554 62. Vallejo, A., Chandra, R. R. & van der Linder, M. *Manual for Monitoring of CDM*
555 *Afforestation and Reforestation Projects - Part I - Standard Operational Procedures.*
556 (World Bank, 2011).
- 557 63. UNFCCC. *Guidelines for the technical review of greenhouse gas inventories from*
558 *parties included in annex I to the Convention.* FCCC/CP/2002/8 (2002).
- 559 64. GHG Protocol. *The Global Protocol for Community-Scale Greenhouse Gas Emissions*
560 *- GPC Pilot Version 1.0.* 14 p (WRI/WBCSD, 2012).
- 561 65. Covenant of Mayors. *How to Develop a Sustainable Energy Action Plan.* 124 p
562 (2010).
- 563 66. ADEME. *Bilan Carbone® Entreprises – Collectivités -Territoires. Guide*
564 *méthodologique - version 6.1 - Objectifs et principes de comptabilisation.* 116 p
565 (Agence de l'Environnement et de la Maîtrise de l'Énergie, 2010).
- 566 67. VCS. *JNR Validation and Verification Process, v3.0.* 14 p (Verified Carbon Standard,
567 2013).
- 568 68. European Commission. *Commission Regulation 600/2012 on the verification of*
569 *greenhouse gas emission reports and tonne-kilometre reports and the accreditation of*
570 *verifiers pursuant to Directive 2003/87/EC of the European Parliament and of the*
571 *Council.* (2012).
- 572 69. Australian Government. *National Greenhouse and Energy Reporting (Measurement),*
573 *Amendment Determination 2013 (No. 1) - F2013L01191.* (2013).

- 574 70. Shenzhen People's Congress. *Specification with guidance for quantification and*
575 *reporting of the organization's greenhouse gas emissions.* (2012).
- 576 71. Journal Officiel de la République Française. *Loi n° 2010-788 du 12 juillet 2010*
577 *portant engagement national pour l'environnement.* (2010).
- 578 72. MEDDE. *Méthode pour la réalisation des bilans d'émissions de Gaz à effet de serre*
579 *conformément à l'article 75 de la loi n°2010-788 du 12 juillet 2010 portant*
580 *engagement national pour l'environnement.* 46 p (Ministère de l'Ecologie, du
581 Développement Durable et de l'Energie, 2012).
- 582 73. CDP. *Guidance for companies reporting on climate change on behalf of investors &*
583 *supply chain members.* 173 p (Carbon Disclosure Project, 2013).
- 584 74. UNFCCC. *CDM Validation and Verification Standard - Version 03.0.* 63 p (2012).
- 585 75. CAR. *Program Manual.* 42 p (Climate Action Reserve, 2011).
- 586 76. VCS. *VCS Standard. Version 3.* 32 p (Verified Carbon Standard, 2012).
- 587 77. ACR. *The American Carbon Registry® Validation and Verification Guideline -*
588 *Version 1.1.* 64 p (American Carbon Registry, 2012).
- 589 78. Journal Officiel de la République Française. *Arrêté du 2 mars 2007 pris pour*
590 *l'application des articles 3 à 5 du décret n° 2006-622 du 29 mai 2006 et relatif à*
591 *l'agrément des activités de projet relevant des articles 6 et 12 du protocole de Kyoto -*
592 *Version consolidée au 02 décembre 2012.* (2012).
- 593 79. VCS. *Jurisdictional and Nested REDD+ (JNR) Requirements - Version 3.1.* 57 p
594 (Verified Carbon Standard, 2013).
- 595 80. UNFCCC. *CDM Project Standard for project design requirements including*
596 *principles of monitoring - version 6.0.* 61 p (2014).
- 597 81. CAR. *Nitrogen Management - Project Protocol, version 1.1.* 138 p (Climate Action
598 Reserve, 2013).
- 599 82. VCS. *Quantifying N2O Emissions Reductions in Agricultural Crops through Nitrogen*
600 *Fertilizer Rate Reduction, v1.0.* 56 p (Verified Carbon Standard, 2013).
- 601 83. ACR. *Methodology for quantifying Nitrous Oxide (N2O) emissions reductions from*
602 *reduced use of nitrogen fertilizer on agricultural crops - Version 1.* 45 p (American
603 Carbon Registry, 2012).
- 604 84. In Vivo. *Méthodologie spécifique aux projets de réduction des émissions de N2O dues*
605 *à la dénitrification des sols agricoles par insertion de légumineuses dans les rotations*
606 *agricoles.* 42 p (2011).
- 607 85. UNFCCC. *Afforestation and reforestation project activities implemented on lands*
608 *other than wetlands - Version 03.0.* 17 p (2013).
- 609 86. UNFCCC. *Afforestation and reforestation of lands except wetlands - Version 2.0.* 15
610 p (2013).
- 611 87. VCS. *VM0010 Methodology for Improved Forest Management: Conversion from*
612 *Logged to Protected Forest - Version 1.2.* 72 p (Verified Carbon Standard, 2013).
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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 ⁽¹⁾ for details.

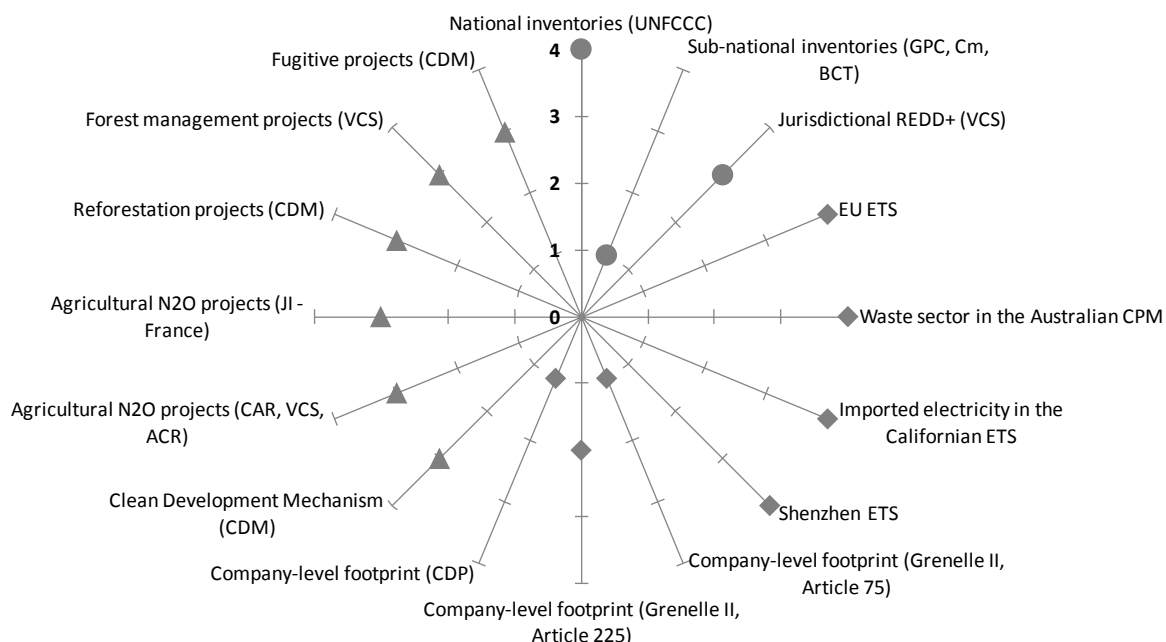
MRV scale		Standard or regulation	Cost per entity (€ yr ⁻¹)	Cost per emission (€ tCO ₂ e ⁻¹)	Share of verification in total MRV costs	Original sources See for ⁽¹⁾ details on the methods for each carbon pricing mechanism.
Jurisdiction	National inventories	United Nations Framework Convention on Climate 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 ^f	no data	no data	55
UNSET project	Projects	Clean Development Mechanism (CDM)	55,000	0.57	32%	32,34,36,37,39,56,57

^f 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 ⁻¹)	Cost per emission (€ tCO ₂ e ⁻¹)	Share of verification in total MRV costs	Original sources See for ⁽¹⁾ details on the methods for each carbon pricing mechanism.
	Agricultural N ₂ 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%	^{33,58-62}
	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%	¹

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

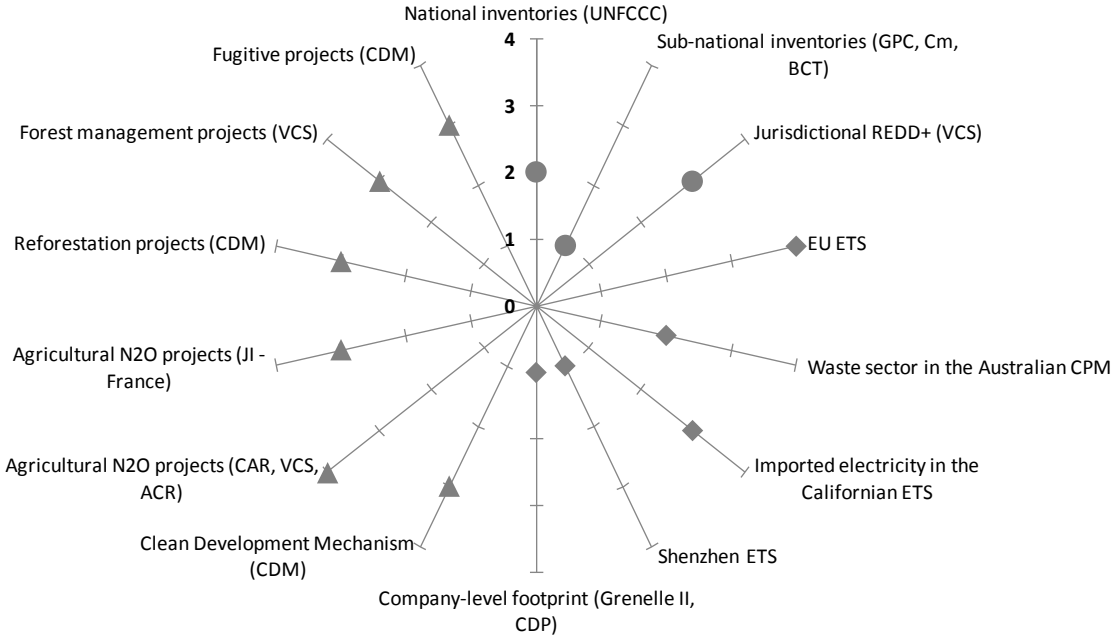
Scale of the CPM

- 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)⁶³, Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC)⁶⁴, Covenant of mayors (Cm)⁶⁵, Bilan Carbone Territorial (BCT)⁶⁶, Verified Carbon Standard (VCS)⁶⁷, Verification Regulation (VR)⁶⁸, National Greenhouse and Energy Reporting Act (NGER)⁶⁹, Mandatory reporting of greenhouse gas emissions regulation (MRR)¹⁵, Specification with guidance for quantification and reporting of the organization's greenhouse gas emissions (SZDB/Z 69)⁷⁰, French Grenelle II law Article 75^{71,72}, French Grenelle II law – Article 225⁷¹, Carbon Disclosure Project (CDP)⁷³, Clean Development Mechanism (CDM)⁷⁴, Climate Action Reserve (CAR)⁷⁵, VCS⁷⁶, American Carbon Registry (ACR)⁷⁷, Joint Implementation (JI) - France⁷⁸, CDM⁷⁴, VCS⁷⁶, CDM⁷⁴.

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%)

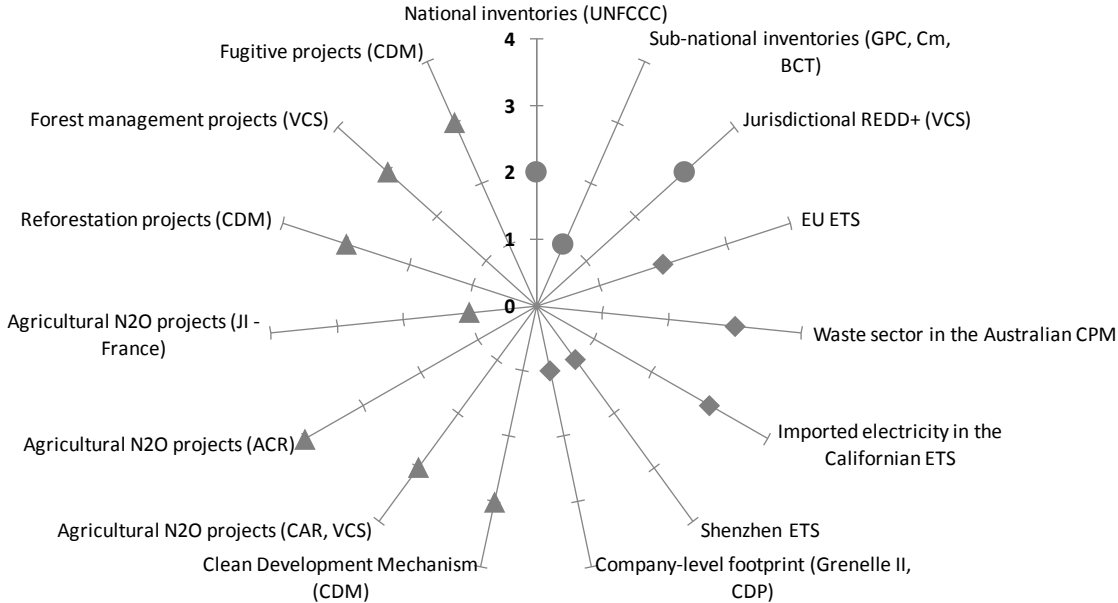
Scale of the CPM

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

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

Sources: UNFCCC⁶, GPC⁶⁴, Cm⁶⁵, BCT⁶⁶, VCS⁷⁹, Monitoring and Reporting Regulation (MRR)¹⁰, NGER⁶⁹, MRR¹⁵, SZDB/Z 69⁷⁰, CDP⁷³, Grenelle II Article 225 & 75^{71,72}, CDM^{11,80}, CAR⁸¹, VCS⁸², ACR⁸³, JI - France⁸⁴, CDM^{85,86}, VCS^{18,87}, CDM¹⁹.

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.

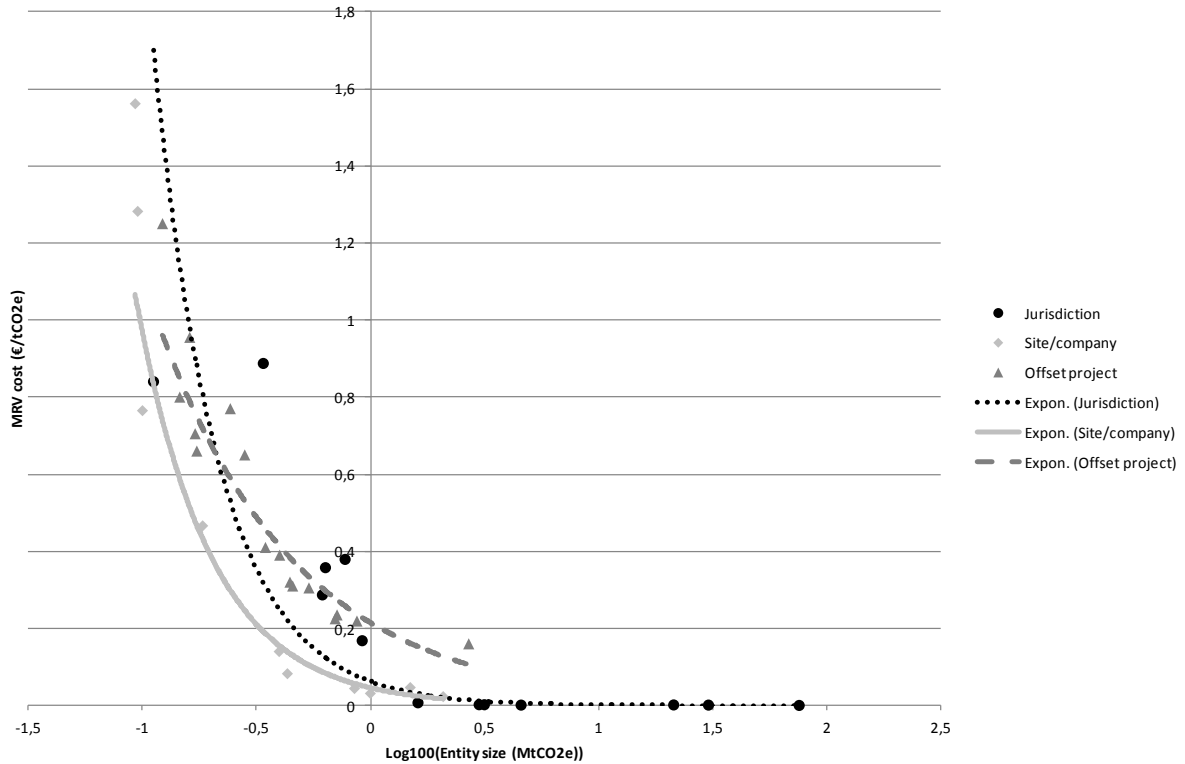
Scale of the CPM

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

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

Sources: UNFCCC⁶, GPC⁶⁴, Cm⁶⁵, BCT⁶⁶, VCS⁷⁹, MRR¹⁰, NGER⁶⁹, MRR¹⁵, SZDB/Z 69⁷⁰, CDP⁷³, Grenelle II Article 225 & 75^{71,72}, CDM⁸⁰, CAR⁸¹, VCS⁸², ACR⁸³, JI - France⁸⁴, CDM^{85,86}, VCS^{18,87}, CDM¹⁹.

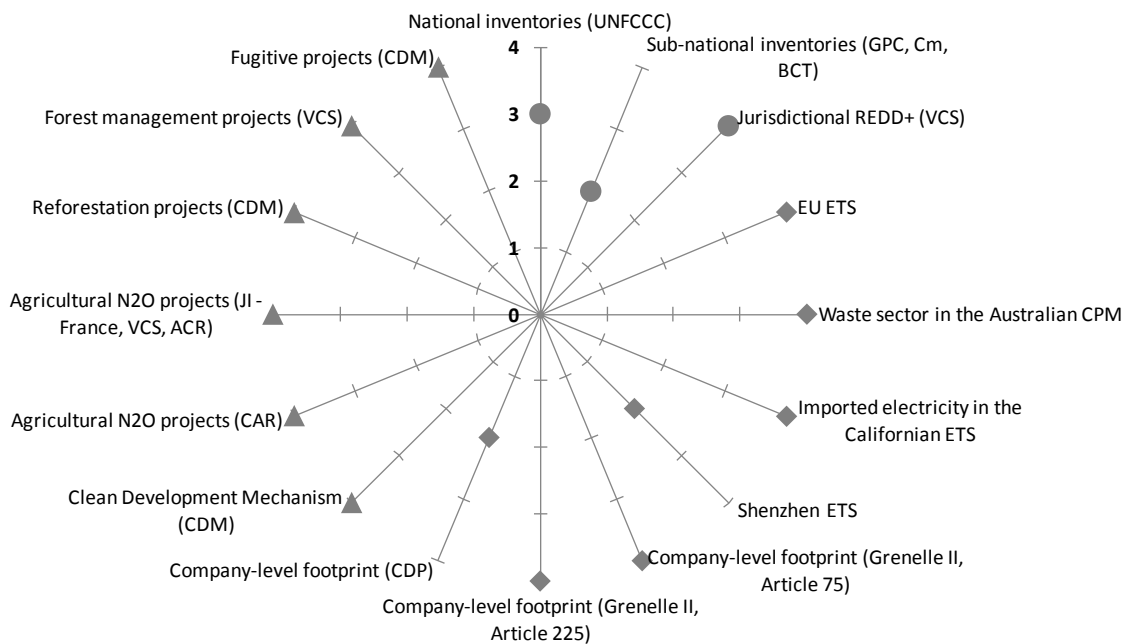
Figure 4. Economies of scale in MRV



Note: Each point corresponds to one of the (cost, size) pairs retained in ⁽¹⁾. 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 ⁽¹⁾.

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: UNFCCC⁶, GPC⁶⁴, Cm⁶⁵, BCT⁶⁶, VCS^{67,79}, MRR¹⁰, NGER⁶⁹, MRR¹⁵, SZDB/Z 69⁷⁰, Grenelle II Article 75⁷¹, Grenelle II – Article 225⁷¹, CDP⁷³, CDM⁸⁰, CAR⁸¹, ACR⁷⁷, VCS⁷⁶, JI⁷⁸, CDM^{74,85,86}, VCS^{18,76,87}, CDM¹⁹.

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 ⁽¹⁾.

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 ₂ 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 ₂ 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 ₂ 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 ₂ 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 ₂ 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)?
Reporting	
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 ₂ e. The precise elements included in this cost estimate are provided on a case by case basis.
Verification	
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 ₂ 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) ²		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) ³ / Covenant of mayors (Cm) ⁴ / Bilan Carbone Territorial (BCT) ⁵		None. However strongly recommended by all reporting guidelines and protocols.	
	Jurisdictional REDD+	Verified Carbon Standard (VCS) ⁶		Variable frequency, performed by a UNFCCC or ISO accredited firm.	
Site/company	EU ETS	Verification Regulation (VR) ⁷		Annual, performed by a firm accredited by the relevant national authority.	
	Waste sector in the Australian CPM	National Greenhouse and Energy Reporting Act (NGER) ⁸		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) ⁹		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) ¹⁰		Annual, performed by a firm accredited by the relevant authority (DRC).	
	Company-level footprint		French Grenelle II law Article 75 ^{11,12}		None.
			French Grenelle II law – Article 225 ¹¹		Annual. Limited to completeness of information and "fairness". No detailed set of guidelines to verify the reports against.
			Carbon Disclosure Project (CDP) ¹³		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) ¹⁴		Variable frequency, performed by a UNFCCC accredited firm.	
	Agricultural N2O projects		Climate Action Reserve (CAR) ¹⁵ / VCS ¹⁶ / American Carbon Registry (ACR) ¹⁷		Variable frequency, performed by a UNFCCC or ISO accredited firm.
			Joint Implementation (JI) - France ¹⁸		Variable frequency, performed by a UNFCCC or EU ETS accredited firm.

Reforestation projects	CDM ¹⁴		Variable frequency, performed by a UNFCCC accredited firm.
Forest management projects	VCS ¹⁶		Variable frequency, performed by a UNFCCC or ISO accredited firm.
Fugitive projects	CDM ¹⁴		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		Qualitative (e.g. key categories should use a country-specific emission factor)		Quantitative, covering a few sources of uncertainty (e.g. sampling error shall be no greater than 10%)		Quantitative, covering most sources 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
Jurisdiction	National inventories	UNFCCC ¹⁹			Key categories must use at least Tier 2. General objective to reduce uncertainty over the long run.
	Sub-national inventories	GPC ³ / Cm ⁴ / BCT ⁵			None.
	Jurisdictional REDD+	VCS ²⁰			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.
Site/company	EU ETS	Monitoring and Reporting Regulation (MRR) ²¹			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 ⁸			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 ⁹			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 ¹⁰			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 ¹³ /Grenelle II Article 225 & 75 ^{11,12}			None.
Offset project	Projects	CDM ^{22,23}			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 ₂ O	CAR ²⁴ / VCS ²⁵ / ACR ²⁶		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).
			Jl - France ²⁷		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 ^{28,29}			Depends on methodologies: either a fixed 10% maximum or a deduction based on the sampling error on tree biomass.
	Forest management projects	VCS ^{30,31}			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 ³²			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		Qualitative (e.g. general principle of "continuous improvement")		Indirect (e.g. through a conservative emission factor) and quantitative, but covering only a few sources of uncertainty.		Direct (e.g. deduction factor) and quantitative, covering most sources 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 ¹⁹			Key categories must use at least Tier 2. General objective to reduce uncertainty over the long run.
	Sub-national inventories	GPC ³ / Cm ⁴ / BCT ⁵			None.
	Jurisdictional REDD+	VCS ²⁰			"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 ²¹			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 ⁸			Incentive to upgrade to method 2 when methane capture is higher than 75%.
	Imported electricity in the Californian ETS	MRR ⁹			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 ¹⁰			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 ¹³ /Grenelle II Article 225 & 75 ^{11,12}		None.
Offset project	Projects	CDM ²³		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 ₂ O	CAR ²⁴ / VCS ²⁵		A deduction is applied if the uncertainty associated with the emission factor exceeds 15%.
		ACR ²⁶		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 ²⁷		None.
	Reforestation projects	CDM ^{28,29}		In some methodologies, a deduction is applied based on the sampling error on tree biomass.
	Forest management projects	VCS ^{30,31}		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 ³²		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
Jurisdiction	National inventories	UNFCCC ¹⁹	None beyond the key category analysis ⁷ .
	Sub-national inventories	GPC ³ / Cm ⁴ / BCT ⁵	None.
	Jurisdictional REDD+	VCS ^{6,20}	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.
Site/company	EU ETS	MRR ²¹	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 ₂ e/yr and 30% below 5 ktCO ₂ e/yr). Simplified requirements for installations below 25 ktCO ₂ 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 ⁸	Inclusion threshold of 25 ktCO ₂ e/yr (or 10 ktCO ₂ e/yr in the vicinity of an already included landfill). Verification is only systematic for facilities above 125 ktCO ₂ e/yr. Smaller installations are verified on an arbitrary basis, to the expense of the regulator.
	Imported electricity in the Californian ETS	MRR ⁹	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 ¹⁰	None.
	Company-level footprint	Grenelle II Article 75 ¹¹	Inclusion thresholds (e.g. private companies with more than 500 employees).
		Grenelle II – Article 225 ¹¹	Inclusion thresholds (e.g. private companies with more than 500 employees and an annual income or assets worth more than € 100 million).
	CDP ¹³	None.	
Offset project	Projects	CDM ²³	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 ₂ e/yr) to 0.5% (> 500 ktCO ₂ e/yr).

⁷ 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 ktCO₂e 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 ₂ O projects	CAR ²⁴	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 ¹⁷ / VCS ¹⁶ / JI ¹⁸	Reporting and Verification frequency is up to the project developer. Materiality threshold between 1% and 5% for VCS during verification.
Reforestation projects	CDM ^{14,28,29}	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 ^{16,30,31}	Depending on the methodology, several sources may be considered de minimis (forestry operations, CH ₄ and N ₂ 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 ³²	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 ₂ e)	Entity size (MtCO ₂ 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 ₂ e yr-1, Aether (2010)	1,28	0,01
	EU ETS	MRR	Installations between 25 and 50 ktCO ₂ e yr-1, Aether (2010)	0,47	0,03
	EU ETS	MRR	Installations between 50 and 500 ktCO ₂ e yr-1, Aether (2010)	0,14	0,16
	EU ETS	MRR	Installations > 500 ktCO ₂ e yr-1, Aether (2010)	0,05	2,24
	EU ETS	MRR	Installations > 1,4 MtCO ₂ e yr-1, Jaraite et al (2010)	1,56	0,01
	EU ETS	MRR	Installations between 0,067 and 1,4 MtCO ₂ e yr-1, Jaraite et al (2010)	0,04	0,73
	EU ETS	MRR	Installations < 67 ktCO ₂ e yr-1, Jaraite et al (2010)	0,02	4,35
	EU ETS	MRR	Installations emitting 10 ktCO ₂ 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 ₂ O nitric acid, Warnecke (2013)	0,305	0,289
	Projects	CDM	N ₂ 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).
2. UNFCCC. *Guidelines for the technical review of greenhouse gas inventories from parties included in annex I to the Convention.* FCCC/CP/2002/8 (2002).
3. GHG Protocol. *The Global Protocol for Community-Scale Greenhouse Gas Emissions - GPC Pilot Version 1.0.* 14 p (WRI/WBCSD, 2012).
4. Covenant of Mayors. *How to Develop a Sustainable Energy Action Plan.* 124 p (2010).
5. ADEME. *Bilan Carbone® Entreprises – Collectivités -Territoires. Guide méthodologique - version 6.1 - Objectifs et principes de comptabilisation.* 116 p (Agence de l'Environnement et de la Maîtrise de l'Energie, 2010).
6. VCS. *JNR Validation and Verification Process, v3.0.* 14 p (Verified Carbon Standard, 2013).
7. European Commission. *Commission Regulation 600/2012 on the verification of greenhouse gas emission reports and tonne-kilometre reports and the accreditation of verifiers pursuant to Directive 2003/87/EC of the European Parliament and of the Council.* (2012).
8. Australian Government. *National Greenhouse and Energy Reporting (Measurement), Amendment Determination 2013 (No. 1) - F2013L01191.* (2013).
9. California Air Resource Board. *ARB Mandatory Reporting Regulation. California Code of Regulations Title 17, CCR, sections 95100 - 95158,* (2013).
10. Shenzhen People's Congress. *Specification with guidance for quantification and reporting of the organization's greenhouse gas emissions.* (2012).
11. Journal Officiel de la République Française. *Loi n° 2010-788 du 12 juillet 2010 portant engagement national pour l'environnement.* (2010).
12. MEDDE. *Méthode pour la réalisation des bilans d'émissions de Gaz à effet de serre conformément à l'article 75 de la loi n°2010-788 du 12 juillet 2010 portant engagement national pour l'environnement.* 46 p (Ministère de l'Ecologie, du Développement Durable et de l'Energie, 2012).
13. CDP. *Guidance for companies reporting on climate change on behalf of investors & supply chain members.* 173 p (Carbon Disclosure Project, 2013).
14. UNFCCC. *CDM Validation and Verification Standard - Version 03.0.* 63 p (2012).
15. CAR. *Program Manual.* 42 p (Climate Action Reserve, 2011).
16. VCS. *VCS Standard. Version 3.* 32 p (Verified Carbon Standard, 2012).
17. ACR. *The American Carbon Registry® Validation and Verification Guideline - Version 1.1.* 64 p (American Carbon Registry, 2012).
18. Journal Officiel de la République Française. *Arrêté du 2 mars 2007 pris pour l'application des articles 3 à 5 du décret n° 2006-622 du 29 mai 2006 et relatif à l'agrément des activités de projet relevant des articles 6 et 12 du protocole de Kyoto - Version consolidée au 02 décembre 2012.* (2012).
19. IPCC. *2006 IPCC guidelines for national greenhouse gas inventories.* (IGES, 2006).
20. VCS. *Jurisdictional and Nested REDD+ (JNR) Requirements - Version 3.1.* 57 p (Verified Carbon Standard, 2013).

21. European Commission. *Commission Regulation (EU) No 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council.* (2012).
 22. UNFCCC. *Standard for sampling and surveys for cdm project activities - version 3.0.* 8 p (2011).
 23. UNFCCC. *CDM Project Standard for project design requirements including principles of monitoring - version 6.0.* 61 p (2014).
 24. CAR. *Nitrogen Management - Project Protocol, version 1.1.* 138 p (Climate Action Reserve, 2013).
 25. VCS. *Quantifying N₂O Emissions Reductions in Agricultural Crops through Nitrogen Fertilizer Rate Reduction, v1.0.* 56 p (Verified Carbon Standard, 2013).
 26. ACR. *Methodology for quantifying Nitrous Oxide (N₂O) emissions reductions from reduced use of nitrogen fertilizer on agricultural crops - Version 1.* 45 p (American Carbon Registry, 2012).
 27. In Vivo. *Méthodologie spécifique aux projets de réduction des émissions de N₂O dues à la dénitrification des sols agricoles par insertion de légumineuses dans les rotations agricoles.* 42 p (2011).
 28. UNFCCC. *Afforestation and reforestation project activities implemented on lands other than wetlands - Version 03.0.* 17 p (2013).
 29. UNFCCC. *Afforestation and reforestation of lands except wetlands - Version 2.0.* 15 p (2013).
 30. VCS. *VM0010 Methodology for Improved Forest Management: Conversion from Logged to Protected Forest - Version 1.2.* 72 p (Verified Carbon Standard, 2013).
 31. VCS. *VM0012 Improved Forest Management in Temperate and Boreal Forests (LtPF) - Version 1.1.* 83 p (Verified Carbon Standard, 2012).
 32. UNFCCC. *Approved baseline and monitoring methodology AM0023 - Leak detection and repair in gas production, processing, transmission, storage and distribution systems and in refinery facilities - Version 04.0.0.* 21 p (2011).
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