J Regul Econ (2012) 42:180–203
DOI 10.1007/s11149-012-9196-1

ORIGINAL ARTICLE

Optimal monitoring of credit-based emissions trading under asymmetric information

Ian A. MacKenzie · Markus Ohndorf

Received: 25 January 2011 / Accepted: 19 May 2012 / Published online: 19 June 2012

Abstract Project-based emissions trading schemes, like the Clean Development Mechanism, are particularly prone to problems of asymmetric information between project parties and the regulator. In this paper, we extend the general framework on incomplete enforcement of policy instruments to reflect the particularities of credit-based mechanisms. The main focus of the analysis is to determine the regulator's optimal spot-check frequency given plausible assumptions of incomplete enforcement under asymmetric information on reduction costs and heterogeneous verifiability of projects. We find that, depending on the actual abatement cost and penalty schemes, optimal monitoring for credit-based systems is often discontinuous and significantly differs from the one to be applied for cap-and-trade schemes or environmental taxes. We conclude that, in a real-world context, project admission should ultimately be based on the criterion of verifiability.

Keywords Environmental regulation · Project-based emissions trading systems · Audits and compliance

JEL Classification K32 · D42 · D82 · Q58

I. A. MacKenzie (✉)
Center of Economic Research, ETH Zürich, 8092 Zurich, Switzerland
e-mail: imackenzie@ethz.ch

M. Ohndorf
Institute for Environmental Decisions, ETH Zürich, 8092 Zurich, Switzerland

1 Introduction

Project-based emissions trading schemes have recently increased in importance due to the successful implementation of the Kyoto markets. These schemes allow project developers, outside the regulation of cap-and-trade schemes, to sell their certified emission reductions on the cap-and-trade market. Indeed, credit-based mechanisms represent the only—although second-best—option to extend emissions trading to countries unwilling to take on emission targets. This is particularly important as within the current Kyoto architecture, these countries have the largest share of low-cost emission reductions. Yet project-based schemes, like the Clean Development Mechanism (CDM), are particularly vulnerable to problems of incomplete enforcement. Information asymmetries between the regulator and project developers create an incentive to overstate emission offsets, sold on the market for emission rights. This problem is often more severe under credit-based systems than standard market-based environmental policy instruments, where cheating is reduced to a misrepresentation of actual emissions. It is, therefore, natural to ask how the regulator determines optimal monitoring policy under a project-based system and how this policy compares to standard market-based regulation.

To answer these questions, we develop an analytical model of a credit-based system that takes potential overreporting of emission reductions into account. We focus on the optimal decisions of the regulator, given the impossibility to fully enforce compliance, under asymmetric information on reduction costs and heterogeneous verifiability of projects. We show, given a limited monitoring budget, a rational regulator will completely refrain from monitoring those projects that are most difficult to verify. For larger monitoring budgets, the optimal monitoring strategy can be discontinuous, featuring a jump within the set of projects with lower verifiability. Furthermore, for those projects in full compliance, the monitoring pressure reduces with increasing verifiability of the projects. For cases with intermediate verifiability, optimal monitoring pressure is ambiguous. For these levels of verifiability, we identify conditions for which monitoring pressure is either at its maximum or for which there exists a 'U-shaped'-style monitoring policy.

Given the importance of enforcing environmental policies, considerations of incomplete enforcement of instruments has become an important research field. Early research mainly focused on the comparison of emission taxes and pollution standards. The first formal model on this issue was developed in Harford (1978), which was extended in Harford (1987) to include self-reporting by firms. Within more recent research the analyses were extended to the comparative performance of different environmental policy instruments under incomplete enforcement. Schmutzler and Goulder (1997) focus on the difference between emission taxes and output taxes. Macho-Stadler and Perez-Castrillo (2006) analyze the optimal enforcement policy in the context of per-unit emission taxes. Further analysis has also been conducted on cap-and-trade programs (Keeler 1991; Macho-Stadler 2006; Malik 1990; Stranlund and Chavez 2000; Stranlund et al. 2005; Stranlund 2007).[1]

[1] For literature surveys on environmental regulation, see Cohen (1999) and Heyes (2000).

Yet, the literature on credit-based systems is sparse.[2] To our knowledge, there exists no formal model deriving optimal monitoring. This is particularly unfortunate in light of the elevated potential for fraudulent misreporting within such schemes. Recently, Macho-Stadler and Perez-Castrillo (2006) analyzed optimal monitoring policy under an emissions tax, assuming the regulator's objective is to minimize the spread between actual emissions and their optimal level. They show that monitoring should be used for the easiest-to-monitor firms as well as firms that value pollution less. Yet when considering credit-based mechanisms, the regulator's objective is different. Not only does the regulator want to minimize *actual* emissions but also the overstatement within projects' *reported* emissions. Further, it is plausible that the regulator only has a rough notion of the true cost of specific types of reduction projects. Our paper, therefore, extends the analysis of regulating emitters with heterogeneous verifiability by Macho-Stadler and Perez-Castrillo (2006) to include the monitoring of credit-based mechanisms with asymmetric information over project cost.

The paper is structured as follows. In the following subsection the general problem of opportunistic false reporting in credit-based systems is explained further. The presentation of the formal model starts with Sect. 2, where the abatement and reporting decisions of a rational project developer are derived. Section 2.2 presents the optimal monitoring policy of a regulator disposing of an unlimited budget. In Sect. 3, optimal monitoring is analyzed under the more realistic assumption of a limited budget and compares this to the case of tax regulation, while Sect. 4 extends the model to discuss project admission. Section 5 has some concluding remarks.

1.1 Background

The basic idea of credit-based emissions trading is to incentivize emission reductions on a project-by-project basis. A prominent example is the Clean Development Mechanism (CDM): a policy tool under the Kyoto Protocol that reduces greenhouse gases in developing countries. Emission reductions generated through projects are scrutinized by the regulator then sold on the carbon market in the form of certified emission reductions (CERs). The importance of the CDM has increased over the last 10 years with aggregated CDM reductions expected to exceed 2.7 billion tonnes of CO_2 equivalents (UNEP/Risoe 2010). The CDM has allowed access to low-cost reduction potentials within developing countries. Yet, generally, the necessity to regulate a project-by-project approach has resulted in high transaction costs. Typically, project certificates are generated by comparing a hypothetical baseline emission scenario with the realized project emission reductions. The difference is then transformed into tradable emission credits. CDM projects, therefore, are required to go through a meticulous process of scrutinization for the project itself, as well as its baseline, before being allowed to generate credits (UNFCCC 2002). For this reason, such schemes can only be recommended for situations where a cap-and-trade regime cannot be implemented.

[2] A notable exception is Sigman and Chang (2011), identifying the basic trade-offs in incomplete enforcement when integrating a credit-based regime into a cap-and-trade market.

This was the case at the conception of the CDM, as developing countries—just as at present—were unwilling to take binding emission reduction targets.

Within credit-based mechanisms, it is plausible that some level of information asymmetry persists between project parties and the regulator. The baseline, for example, should ideally represent the scenario without project implementation. Clearly, any alternative plans for the project site are, by definition, private information, which is a priori unobservable to the regulator. Hence, there exists an incentive to submit a baseline scenario to the regulator, which leads to an overstatement of emission reductions, and hence more credits. A prominent case where such a practice has been identified ex post, is associated with a reduction of hydrofluorocarbons (HFC)—a potent greenhouse gas—in China (Wara 2007, 2008). Due to incorrect estimates of cost structures and market forecasts, baseline emissions were too generous. As a consequence, the CDM Executive Board halted issuance for such projects and the European Commission decided to ban CERs from HFC projects within the EU ETS from 2013 onwards.[3] Note that this baseline information asymmetry is hence fundamental to the issue of *additionality* within the CDM: the risk that certificates might not represent *actual* emission reductions.

It is also reasonable to assume that some project types are easier to identify as being additional than others. Solar projects, for example, are—due to their relatively high per unit cost—more likely to be additional than the reduction of industrial gases, which can often be easily substituted by other substances.[4] Furthermore, due to differences in data quality, future developments in product markets are easier to assess in some host countries than in others. A regulator's monitoring strategy, then, has to take these differences in project verifiability into account.

The risk of fraudulent non-compliance is not limited to credit-based mechanisms, but represents, in fact, a problem for any type of environmental regulation. For example, in a cap-and-trade emissions trading system, potential net buyers might be tempted to *report* compliance with their emissions target to avoid purchasing emission credits.[5] Obviously, as emission permits have a positive market value, such overreporting also benefits net sellers, which can increase their revenues from emission rights. As a consequence, due to the risk of opportunistic misreporting, an environmental policy needs to include an enforcement mechanism to be effective. An environmental regulator is hence mandated to ensure environmental effectiveness and carry out costly monitoring activities in order to reduce the amount of misreporting. However, in a resource-constrained world, monitoring and enforcement is likely to be incomplete. For these cases, Macho-Stadler and Perez-Castrillo (2006) show that a regulator, which discriminates between the verifiability of emission reports, should accept an arbitrarily large amount of overreporting and opt instead for a monitoring strategy that induces the largest portion of emitters to reduce emissions to their optimal level.[6]

[3] See, for example, WorldBank (2011).

[4] See, for example, Wara (2008, 2007).

[5] A similar rationale applies in the case of a per-unit tax on emissions, as the reported emissions represent the basis from which the overall tax burden for the regulated entity is derived.

[6] Obviously, such a strategy is only necessary if the optimal amount of emissions diverges from the 'maximum believable' amount, which will be reported by most emitters in such a situation.

For credit-based emissions trading, however, the use of such a strategy will not minimize emissions in the overall emissions market. To see this, note that the demand for offset credits is typically stemming from an associated cap-and-trade regime. The CDM is, for instance, linked into both the Kyoto inter-country cap-and-trade market and the European Union Emissions Trading System (EU ETS). Due to the fungibility between emission permits (e.g. EIT AAUs from EU ETS) and emission credits (e.g. CDM CER), the latter has a positive value driven by the permit market price. Fungibility, however, also means that an offset credit that is not backed by an *actual* emission reduction, but created by fraudulent overreporting at zero cost, will crowd out more expensive reductions within the system.[7] Note further that this crowding out is unlikely to have a large effect on prices, as cap-and-trade markets tend to be significantly larger than the credit-based mechanisms. For example, the market volume of the EU ETS in 2010 was reported to be about 119 billion USD, while the size of the primary CDM market amounted only to 1.5 billion USD (WorldBank 2011). In the political discussion, the problem of erroneous or non-additional credits represents the main argument against the continuation of such schemes. However, as long as the gains from the realized emission reductions are larger than the cost of implementation, the credit-based mechanisms will continue to play an important role when cap-and-trade schemes are infeasible.[8]

The existence of the above-described crowding out of legitimate permits by erroneous credits requires a regulator to minimize emissions within the combined market, which requires a different monitoring strategy than the one depicted in Macho-Stadler and Perez-Castrillo (2006). For credit-based schemes, the regulator cannot confine himself to guarantee efficient levels of emission reductions, but also needs to reduce overreporting to minimize the amount of erroneous credits in the whole system. In the following, we present a model, to derive the optimal monitoring within a credit-based emissions trading regime.

2 The model

Consider a regulated credit-based emissions trading scheme, populated by a set of project developers $\Phi = \{1, 2, \ldots, n\}$ with cost type $j = \{g, b\}$, which choose levels of emission reductions e at a cost $c_j(e)$ with $c'_j(e) > 0$, $c''_j(e) > 0$, $\forall\ e$. For any level of emission reductions e, projects of type g and b differ in abatement costs by $c_g(e) < c_b(e)$ and $c'_g(e) < c'_b(e)$. That is, for a given level of emissions reductions, (marginal) abatement costs are larger for a 'bad' b-type than a 'good' g-type.[9] The

[7] The situation resembles a 'market for lemons', while differing by the fact that a credit only loses its value if it is identified as erroneous by the regulator.

[8] In the current international climate policy negotiations, creditable NAMAs (Nationally Appropriate Mitigation Actions) are discussed in order to incentivize emission reductions in developing countries (see, for example, Okubo et al. (2011)).

[9] This differentiation in cost types might well occur within one specific class of projects, implementing the same type of technology. For example, two windpower generation projects designed to replace coal-based power generation might install exactly the same type of equipment and capacity, but differences in average wind speed at the chosen projects sites could still lead to a difference in abatement costs.

cost functions are common knowledge whereas the cost type is private information to the project developer. The regulator is assumed to know the relative frequency of a g-type given by π, while a b-type occurs with converse probability $(1 - \pi)$.

Where actual project reductions are fully observable and enforceable, each project participant selects emission reductions so that $c'_b(e^*_b) = c'_g(e^*_g) = p$ and hence $e^*_b < e^*_g$, where p is the equilibrium permit price and e^*_j is the resulting first-best optimal level of emission reductions for type j. This represents the well-known result that under perfect competition with complete information, marginal abatement costs are equated to the equilibrium certificate price.

2.1 Project decision under asymmetric information

A more realistic setup is to assume that neither the project's cost type j nor the chosen level of emission reduction e_j are directly observable by the regulator. Instead, to receive reduction credits, the project developer submits a report over emissions reductions z_j, which does not necessarily correspond to the emission level actually chosen. Note that, with rational actors, reported emission reductions z_j will never be less than the actual reductions e_j. However, as certificates command value, the developer might be tempted to overreport emission reductions, such that $z_j > e_j$ is possible. However, given that the regulator knows (or has an adequate notion of) the cost functions and the market price, he will never accept a report larger than e^*_g, the level of 'good'-type reductions under full observability. While 'bad'-type projects can mimic a 'good' type in reporting, 'good' types are limited to simple overreporting, which would be the case if $e_g < e^*_g$ but $z_g = e^*_g$ is reported.

In order to induce truthful reporting, the regulator has the possibility to monitor projects.[10] We assume that even if monitored with probability 1, verifiability of the report differs over different classes of projects. For example, the baseline of a solar project is easier to verify than for projects reducing industrial greenhouse gases.[11] To reflect this, we assume that each class of projects is associated with a commonly observable class-specific parameter $\beta \in [0, 1]$, reflecting its verifiability. If β is 1 and the project is monitored, the regulator is capable to determine, without further problems, whether the project developer has overreported or not. As β tends to 0, the more improbable is the success of such an assessment. For the sake of simplicity, we assume class designator β to be uniformly distributed with density function probability function $F(\beta) = \beta$ and density $f(\beta) = 1$. This distribution is common knowledge.[12] Given

[10] In the context of the Clean Development Mechanism, the role of the regulator is taken up by the CDM Executive Board and its supporting panels. As a consequence, the decisions of the external verifiers—the Designated Operational Entities—are not explicitly modeled here. This simplification is justifiable on the grounds that the CDM verification mechanism is not capable to fully deter opportunistic overreporting (Wara 2007, 2008). This incomplete deterrence can also be attributed to the fact that the DOEs are remunerated by the project participants, potential collusion in reporting of emission reductions cannot be excluded.

[11] Heyes (1994) provides further reasoning for divergence in verifiability levels. In particular, Heyes (1994) considers the case where firms can endogenously determine their 'inspectability' by investing in appropriate technologies.

[12] Alternatively, the regulator can be assumed to have no information about the underlying distribution, and assumes for lack of that knowledge, that β is uniformly distributed.

that the class of a project is observable, the regulator can discriminate among classes in his monitoring decision. For each project class the regulator chooses a monitoring probability $\alpha(\beta)$, with $\alpha \in [0, 1]$. It is assumed that this probability is known to the project participants. For example, in reality, α would be determined by the expected frequency of 'spot-checks' on each project class by the regulator.

In case overreporting is discovered, project developers are required to pay back the revenue from overreported reductions and, *in addition*, pay a fine. The regulator is assumed to make the fine contingent on the overreported amount x_j, defined as $x_j = z_j - e_j$. If a project is monitored its expected penalty is hence dependent on its verifiability class β and the overreported amount x_j. We define this expected penalty as $\beta \cdot \theta(x_j)$, with $\theta(0) = 0$, $\theta'(\cdot) > 0$, $\theta''(\cdot) > 0$, and $\theta'(0) > p$. The assumptions $\theta'(\cdot) > 0$ and $\theta'(0) > p$ ensure that a non-compliant developer that is caught will always pay an amount larger than his revenue generated by overreporting, i.e., $p \cdot x$. Hence, in case of proven overreporting the developer has to return the unlawfully acquired amount plus an additional fine. Note that this fine is increasing in the overreported amount, as $\theta''(\cdot) > 0$. Assuming the expected penalty to be convex in the magnitude of the offense is quite realistic, as it seems to be in line with legal practice under many different circumstances.[13] Furthermore, it is plausible that not only the fine, but also the probability of discovery for any project of class β is increasing and convex in x, which would be also reflected in our formulation of the expected penalty.

For the choice of class-specific monitoring pressure $\alpha(\beta)$, we assume the regulator anticipates the project participant's optimization given the respective level of monitoring. In order to present this choice, we first describe the project developers' optimization over e_j and z_j for an unspecified level of $\alpha(\beta)$ and then discuss the characteristics of $\alpha(\beta)$ for a regulator taking these optimal choices into account.

Note that for reasons explained above, a project developer cannot report a reduction level larger than e_g^*. Given that the regulator knows the technologies that are in the market, there exist only two plausible levels of emission reductions that can be reported without raising the regulator's suspicion, e_g^* and e_b^*.[14] With these restrictions, the developer's optimization problem for a project of verifiability class β and cost type j are

$$\max_{\{e_j, z_j\}} U_j(e_j, z_j) = \left\{ pz_j - c_j(e_j) - \alpha(\beta) \cdot \beta\, \theta(z_j - e_j) \right\} \tag{1}$$

subject to

$$z_b, z_g \in \left\{ e_b^*; e_g^* \right\},$$

[13] The assumption of convex punishment is widely used in a large part of the literature on incomplete enforcement (Harford 1978, 1987; Sandmo 2002; Cremer and Gahvari 2002; Macho-Stadler and Perez-Castrillo 2006). In the context of the CDM, the regulator has the power to 'freeze' future certificate flows—and hence revenue—from a non-compliant project. It is hence likely that there exists a penalty beyond simple compensation for invalidated certificates.

[14] Note that the results are qualitatively similar when $n > 2$ costs types are used. In this case, there would be n discontinuities.

where p is the exogenous permit price, and e_g^* and e_b^* are the first-best efficient levels of emission reductions for 'good' and 'bad' types, respectively. The constraint $z_b, z_g \in \left\{e_b^*; e_g^*\right\}$ reflects that, given the developer's optimization is known to the regulator, only reports corresponding to optimal emission levels would signal compliance. Given that under full compliance a firm would always reduce either e_g^* or e_b^*, the regulator could automatically infer from a report $z \notin \left\{e_b^*; e_g^*\right\}$ that the project is in non-compliance. While this inference would not reveal the degree of overreporting, i.e. $x = z - e$, the regulator is capable to refuse a priori the issuance of certificates. This is realistic, as in many real-world regimes the regulator can refuse to issue certificates if inconsistencies in the report are discovered. Hence, while a report $z \notin \left\{e_b^*; e_g^*\right\}$ does not trigger any penalty payment, a rational developer will always refrain from submitting such a report, as in this case his income would be zero.[15]

It is taken into account within the cost function that in case overreporting is discovered, project developers will have to return excess certificates and pay a fine according to the expected progressive penalty schedule $\theta(x)$. The first-order conditions for (1) with respect to e_j are

$$\frac{\partial U_b}{\partial e_b} = -c_b'(e_b) + \alpha(\beta) \cdot \beta\, \theta'(z_b - e_b) = 0, \tag{2}$$

$$\frac{\partial U_g}{\partial e_g} = -c_g'(e_g) + \alpha(\beta) \cdot \beta\, \theta'(z_g - e_g) = 0. \tag{3}$$

By use of (1) to (3), we can characterize the optimal solution for different levels of $\alpha(\beta)$. From (1), if $\alpha(\beta) \cdot \beta = 0$ the developer's payoff is maximized at $z_j = e_g^*$ and $e_j = 0$, that is, at the maximum possible amount of overreporting. Note that, in principle, a regulator could infer this maximum level of non-compliance from $\alpha\beta = 0$, and automatically apply the maximum sanction $\theta(e_g^*)$ in such a case. However, this would represent a sweeping judgment without proof. As we assume the regulator being bound be the basic principles of the rule of law, we explicitly exclude the possibility of such an inference.[16] From (1), when values of $\alpha\beta$ are close enough to 0, it is efficient for both types to increase emission reductions while continuing to report the highest plausible reduction, i.e. $z_j = e_g^*$. This is the case as long as

$$U_j(e_j, e_g^*) > U_j(e_j, e_b^*). \tag{4}$$

It is hence to be shown at what level of $\alpha(\beta)$ both types prefer to report e_b^* rather than e_g^*. Starting with 'bad' types, assume, for a moment, that (4) holds at the level of $\alpha(\beta)$

[15] An alternative procedure would be to assume that such an inference is for some reason not feasible. In these cases, as shown in Macho-Stadler and Perez-Castrillo (2006) and Ohndorf (2010), non-compliant agents would, with increasing $\alpha\beta$, first report the maximum plausible level of abatement and reduce emissions until $C'(e) = p$. Only when $e = e^*$ is reached, will the report z begin to reduce toward full compliance ($z = e^*$). Note, however, that there exists in fact no reason to a priori assume the infeasibility of the inference depicted above.

[16] In the context of the CDM, the regulator is indeed bound by these principles, as it has to answer to the Conference of the Parties of the Kyoto Protocol (UNFCCC 2002, Decision 17, Annex, para. 5.).

at which b-types are induced to choose their first-best level of emissions ($e_b = e_b^*$). Then, from (2) and noticing $c_b'(e_b^*) = p$, we can derive a threshold level $\hat{\alpha}(\beta)$ at which $z_b = e_g^*$ and $e_b = e_b^*$, which is defined as

$$\hat{\alpha}(\beta) \equiv \frac{p}{\beta \cdot \theta'(e_g^* - e_b^*)}.$$

Interestingly, at auditing pressure $\hat{\alpha}(\beta)$ condition (4) is indeed fulfilled for b-types, as the latter requires

$$\alpha(\beta) < \frac{p \cdot (e_g^* - e_b^*)}{\beta\theta(e_g^* - e_b^*)}. \tag{5}$$

It is easy to see that this condition always holds at $\hat{\alpha}(\beta)$, as penalty $\beta\theta(\cdot)$ is assumed to be convex. Hence 'bad'-type projects will continue to pretend to be of 'good' type by choosing $z_b = e_g^*$. Given $c_g'(e_b^*) < c_b'(e_b^*) = p$, condition (4) will also always hold for 'good' type projects, such that 'good' types will always report their first-best levels, i.e. $z_g = e_g^*$.

Interestingly, at $\hat{\alpha}(\beta)$ inequality (5) is strict. With further increases in $\alpha(\beta)$ there exists a range within which 'bad' type project developers will choose to further increase emission reductions beyond the first-best levels e_g^* instead of choosing to report truthfully: there exists a range of 'over-reduction', up to a level $\bar{e}_b > e_b^*$, at which $U_b(\bar{e}_b, e_g^*) = U_j(e_b^*, e_b^*)$. From this we can derive another threshold $\breve{\alpha}(\beta)$ defined as follows

$$\breve{\alpha}(\beta) \equiv \frac{p \cdot (e_g^* - e_b^*)}{\beta\theta(e_g^* - \bar{e}_b)}.$$

Threshold $\breve{\alpha}(\beta)$ represents the minimum audit probability that induces a report $z_b = e_b^*$, i.e. truthful reporting of a b-type. Note, this probability level is only feasible if $\breve{\alpha} \leq 1$. We denote the lowest feasible level of verifiability with $\breve{\beta}$, where $\breve{\alpha}(\breve{\beta}) = 1$, which is defined by

$$\breve{\beta} \equiv \frac{p \cdot (e_g^* - e_b^*)}{\theta(e_g^* - \bar{e})}.$$

Finally, as 'good' types will always report $z_g = e_g^*$, full compliance of g-type projects are obtained for levels of α high enough to implement $e_g = e_g^*$. Again, the threshold $\tilde{\alpha}(\beta)$ that implements truthful reporting of a g-type can be derived from (3) and by taking into account $c_g^{'}(e_g^*) = p$, $\tilde{\alpha}(\beta)$ is defined as

$$\tilde{\alpha}(\beta) \equiv \frac{p}{\beta\theta'(0)}.$$

Again, this probability level is only feasible if $\tilde{\alpha} \leq 1$, i.e. $\beta \geq \tilde{\beta}$, where $\tilde{\beta}$ is defined by $\tilde{\alpha}(\tilde{\beta}) = 1$. Threshold $\tilde{\beta}$ is hence

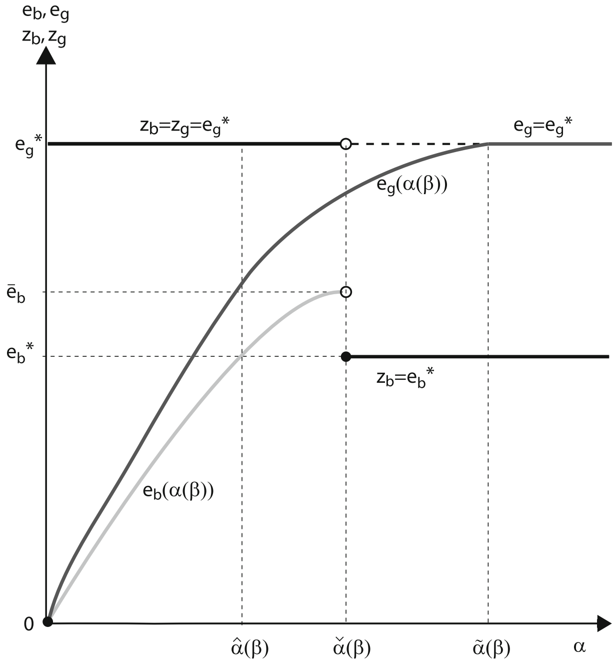

Fig. 1 Reported and actual emission reductions for both cost types

$$\tilde{\beta} \equiv \frac{p}{\theta'(0)}.$$

Note that under the above-made assumptions, for any given β, $\hat{\alpha}(\beta) < \check{\alpha}(\beta) < \tilde{\alpha}(\beta)$. Hence, there exists full compliance for all projects for which $\alpha(\beta) \in [\tilde{\alpha}, 1]$. Summarizing the above-made considerations, Fig. 1 depicts the compliance behavior of 'good'- and 'bad'-type projects in dependence of monitoring probability α.

2.2 Regulator's optimal monitoring policy with an unlimited budget

Given the optimizing behavior of project participants, a regulator needs to identify an optimal monitoring strategy.[17] In order to model the monitoring decision with an existing project pool, the regulator is assumed to face a population of already registered projects. For simplicity, the cost of monitoring one project is normalized to one. Aggregated monitoring cost cannot transgress the regulator's monitoring budget, denoted with B.

Without discovery of non-compliance, a project is issued emission reduction certificates corresponding to its reported amount z_j. As explained in Sect. 1.1, credits not backed by actual emission reductions are non-additional and hence reduce the

[17] For a discussion on how regulatory attitudes alter monitoring policy and environmental innovation, see the recent work of Heyes and Kapur (2011).

environmental integrity of the overall carbon market. The regulator minimizing emissions in the integrated system can hence not confine himself to maximize aggregated emission reductions, but also has to take the problem of overreporting into account. Hence, the objective of the enforcement agency within the setup presented here is to minimize aggregated overreporting, while maximizing emission reductions.

As depicted in Fig. 1, for small α and any given β a change in monitoring pressure only influences emission reductions e_j, while z_j remains—for both cost types—at its corner solution e_g^*. For b-type projects, a further increase in α will only lead to an adjustment of z_b to its truthful level e_b^* after the emission reductions have reached their optimal level. As for g-types, the corner solution for z_g is equal to e_g^*, where overreporting is only reduced to zero if the emission reductions reach exactly this level. This behavior of the project developers simplifies the formulation of the regulator's objective function. If the regulator minimizes weighted aggregations of overreporting $x_j = z_j - e_j$ over all classes of β, he will also achieve a maximization of emission reductions. Hence, the enforcement agency chooses the monitoring schedule $(\alpha(\beta))_{\beta\in[0,1]}$ that solves the following program.

$$\min \int_0^1 \Big(\pi(e_g^* - e_g(\alpha\beta)) + (1-\pi)(z_b(\alpha\beta) - e_b(\alpha\beta))\Big)\, d\beta \tag{6}$$

such that

$$\int_0^1 \alpha(\beta)\, n\, d\beta \leq B \tag{7}$$

and

$$e_g(\beta) \in \operatorname{argmax}\ \left\{U_g(e_g)\right\}, \tag{8}$$

$$e_b(\beta), z_b(\beta) \in \operatorname{argmax}\ \{U_b(e_b, z_b)\}. \tag{9}$$

To choose an optimal monitoring scheme, the agency needs to take into account its budget constraint (7), and the profit maximization of the project participants (8) and (9). Within this subsection we only consider the latter two constraints to be binding.

We denote the minimum budget incentivizing maximum emission reductions by $\bar{B}$, which is defined by:

$$\bar{B} \equiv \tilde{\beta}\, n + \int_{\tilde{\beta}}^1 \tilde{\alpha}(\beta)\, n\, d\beta. \tag{10}$$

Proposition 1 immediately follows:

Proposition 1 *When $B \geq \bar{B}$ the cost-minimizing agency sets an audit policy that satisfies $\alpha(\beta) = 1$, for $\beta \in [0, \check{\beta})$ and $\alpha(\beta) \in [\check{\alpha}(\beta), 1]$ for $\beta \in [\check{\beta}, 1]$.*

Proposition 1 confirms similar findings to the case with emissions taxes. When a scheme includes projects with large information asymmetries between project participants and the regulator, an increase in budget does not necessarily lead to a reduction in overreporting. As soon as the budget level $\bar{B}$ is reached, the marginal rate of deterrence equals zero. Hence, even if a maximization of reductions is the only objective of the agency, efficiency requires that the auditing budget of the regulator should be capped at $\bar{B}$.

3 Monitoring with a limited budget

In practice, it is likely that the number of audits performed by the regulator is constrained by his budget. It is hence realistic to assume that the budget constraint (7) of the regulator's optimization problem is binding. Thus, in the following it is assumed that $B \leq \bar{B}$.

Within a budget-constrained optimization, the regulator needs to decide which β classes should experience an increase in spot-check frequency to obtain the largest decrease in overall emissions. As the regulator cannot observe a project's cost type, the expected amount of overreporting by a project of class β for a given level of α, denoted by $\epsilon_\beta(\alpha)$, is

$$\epsilon_\beta(\alpha) = \Big(\pi(e_g^* - e_g(\alpha\beta)) + (1-\pi)(z_b(\alpha\beta) - e_b(\alpha\beta))\Big). \tag{11}$$

For any two projects with class β_1 and β_2, a shift in monitoring effort of $\Delta\alpha$ from project class 1 to project class 2 is (weakly) efficient if

$$\big[\epsilon_{\beta_2}(\alpha_2 + \Delta\alpha) - \epsilon_{\beta_2}(\alpha_2)\big] - \big[\epsilon_{\beta_1}(\alpha_1) - \epsilon_{\beta_1}((\alpha_1 - \Delta\alpha))\big]\,(\geq) > 0, \tag{12}$$

with

$$\epsilon_\beta(\alpha) = \begin{cases} e_g^*, & \text{for } \alpha(\beta) = 0, \\ \pi(e_g^* - e_g(\alpha\beta)) + (1-\pi)(e_g^* - e_b(\alpha\beta)), & \text{for } 0 < \alpha(\beta) < \check{\alpha}(\beta), \\ \pi(e_g^* - e_g(\alpha\beta)), & \text{for } \check{\alpha}(\beta) \leq \alpha(\beta) < \tilde{\alpha}(\beta), \\ 0, & \text{for } \tilde{\alpha}(\beta) \leq \alpha(\beta) \leq 1, \end{cases} \tag{13}$$

where the case separation in (13) is determined through the optimal reaction of the project developer. An auditing schedule $(\alpha(\beta))_{\beta\in[0,1]}$ is efficient if (12) holds for any arbitrary pairwise comparison of two different project types.

Hence, determining the optimal auditing policy involves a trade-off in monitoring pressure in the range $0 < \alpha < \tilde{\alpha}$. Note that $\epsilon_\beta(\alpha)$ is discontinuous at $\check{\alpha}(\beta)$, i.e. the threshold at which b-types start to truthfully report $z_b = e_b^*$. Above and below this threshold level, $\epsilon_\beta(\alpha)$ is differentiable with respect to α. The derivative of ϵ can be derived from (2), (11), and (13) by applying the Implicit Function Theorem. The corresponding derivative is:

$$\frac{d\epsilon_\beta}{d\alpha} = \begin{cases} \beta \cdot \Big(\frac{\pi \cdot \theta'(e_g^* - e_g(\alpha\beta))}{c_g''(e_g(\alpha\beta)) + \alpha\beta\theta''(e_g^* - e_g(\alpha\beta))} \\ + \frac{(1-\pi)\cdot\theta'(e_g^* - e_b(\alpha\beta))}{c_b''(e_b(\alpha\beta)) + \alpha\beta\theta''(e_g^* - e_b(\alpha\beta))} \Big), & \text{for } \alpha < \check{\alpha}(\beta), \\ \beta\, \pi \cdot \frac{\theta'(e_g^* - e_g(\alpha\beta))}{c_g''(e_g(\alpha\beta)) + \alpha\beta\theta''(e_g^* - e_g(\alpha\beta))}, & \text{for } \check{\alpha}(\beta) \le \alpha \le \tilde{\alpha}(\beta), \\ 0, & \text{for } \alpha > \tilde{\alpha}(\beta), \end{cases} \tag{14}$$

which is used to derive the following proposition.

Proposition 2 *Under a limited budget $B < \overline{B}$, optimal monitoring policy implies that there exists a threshold $\beta_l(B) > 0$, such that the regulator chooses $\alpha = 0$ for $\beta \le \beta_l(B)$. Projects with $\beta > \beta_l(B)$ will always be monitored with $\alpha > 0$.*

Proof See appendix. □

Proposition 2 states that there exists a threshold level $\beta_l(B)$ where lower verifiable projects will not be monitored, whereas all other projects will receive a positive probability of monitoring. This threshold tends to decrease with larger levels of budget B, but will always exist for $B < \overline{B}$. This is in line with the optimal monitoring under an emissions tax, presented in Macho-Stadler and Perez-Castrillo (2006).

Due to the discontinuity at $\check{\alpha}(\beta) = \frac{p\cdot(e_g^* - e_b^*)}{\beta\ \theta(e_g^* - \bar{e}_b)}$ in (14), optimal monitoring cannot be simply assessed via an equalization of the derivatives $\frac{d\epsilon}{d\alpha}$ for different levels of β, as we must take into consideration the change in expected overreporting ϵ that occur exactly at this discontinuity. In particular, for any β, the gain from monitoring a b-type when increasing $\alpha(\beta)$ from 0 to $\check{\alpha}(\beta)$, is e_g^*, which consists of emissions reduction e_b^* as well as the reduction in over-reporting $e_g^* - e_b^*$. For g-type projects, the same increase in monitoring pressure yields an increase in emission reductions of $e_g(\check{\alpha}(\beta) \cdot \beta) = e_g(1 \cdot \check{\beta})$. Thus, the expected gains per unit of α from spending exactly $\check{\alpha}(\beta)$ for any level of $\beta > \check{\beta}$, designated with $D(\beta)$ are:

$$D(\beta) = \frac{\pi\ e_g(\check{\beta}) + (1-\pi)\ e_g^*}{\check{\alpha}(\beta)} = \frac{\beta\ \theta(e_g^* - \bar{e}_b)}{p \cdot (e_g^* - e_b^*)} \cdot (e_g^* - \pi(e_g^* - e_g(\check{\beta}))). \tag{15}$$

Obviously, from (12), it is safe to state that the regulator will choose at least $\check{\alpha}(\beta)$ for a specific project type β, if $D(\beta)$ is larger than any $\frac{d\epsilon}{d\alpha}$ at all other combinations of $\alpha(\beta)$ and β. Note from (14) that the largest marginal benefit in reduction of overreporting is at $\alpha = 0$, $\beta = 1$. On the other hand, the minimum (feasible) level of $\check{\alpha}(\beta)$ lies at $\beta = \check{\beta}$. This allows us to establish a sufficient condition for which it is always efficient to incentivize truthful reporting of 'bad' types for projects with $\beta \in \left[\check{\beta}, 1\right]$:

$$D(\check{\beta}) > \frac{d\epsilon_1(0)}{d\alpha} \iff \pi e_g(\check{\beta}) + (1-\pi)e_g^* > \theta'(e_g^*)\left(\frac{\pi}{c_g''(0)} + \frac{1-\pi}{c_b''(0)}\right). \tag{16}$$

In order to assess the conditions under which (16) holds we introduce a measure γ, representing the relative frequency of a b-type in relation to g-type projects:

$$\gamma \equiv \frac{1-\pi}{\pi}. \tag{17}$$

Obviously, the larger γ, the more imminent is the problem of asymmetric information over reduction costs. This allows us to reformulate (16) as follows:

$$\gamma > \frac{c_b''(0)}{c_g''(0)} \cdot \frac{c_g''(0)\, e(\check{\beta}) - \theta'(0)}{\theta'(0) - c_b''(0) e_g^*}. \tag{18}$$

For a large enough share of b-type projects in the market, the regulator will always use his budget to induce truthful reporting within b-type projects in the verifiability classes, where this is possible, i.e. for $\beta \geq \check{\beta}$. As it is sensible to consider situations with an imminent problem of asymmetric information over types, we assume (18) to hold throughout the rest of this paper. Based on this assumption, the following proposition can be established immediately by noting (7), and the equivalence of (16) and (18):

Proposition 3 *If* (18) *holds, then*

(i) If $B > \check{\alpha}(1) \cdot n$, there exists a $\beta_m \geq \beta_l$, such that $z_b = e_b^*$ for all $\beta \geq \beta_m$. The value of β_m is non-decreasing in B.

(ii) For $B = \int_{\beta_0}^{1} \check{\alpha}(\beta)\ n\ d\beta$ with $\check{\beta} < \beta_0 < 1$, the regulator will incentivize truthful reporting for bad type projects, by choosing an audit pressure of $\check{\alpha}$ for all projects with $\beta \geq \beta_0$. Projects with $\beta < \beta_0$ will not be monitored. Hence, $\beta_m = \beta_l = \beta_0$.

(iii) For $B \geq \int_{\check{\beta}}^{1} \check{\alpha}(\beta)\ n\ d\beta$ the regulator will always incentivize truthful reporting for bad type projects over the range of projects where this is possible, i.e. $\beta \in [\check{\beta}, 1]$.

Proposition 3 further specifies the characteristics of an optimal monitoring schedule for credit-based systems. Proposition 3 (i), establishes the existence of a threshold level β_m where full compliance of 'bad' types is induced for larger β. When the monitoring budget becomes larger than that required to ensure full compliance in the class easiest to verify (i.e. $\beta = 1$), the regulator will induce $z_b = e_b^*$, starting with highest levels of β and continuing to do so for decreasing β, as long as this is feasible within the given budget. It is hence optimal to refrain from monitoring projects of lower levels of β. This is shown within Proposition 3 (ii), where for the sake of simplicity, no residual budget exists.[18] Finally, Proposition 3 (iii) explains that if the budget is sufficiently large to enable the regulator to induce $z_b = e_b^*$ for all classes where this is feasible, it is indeed optimal to do so.

Given these insights, the question arises of how larger budgets should be allocated, which go beyond the level necessary to induce truthful compliance of 'bad' types for

[18] For the sake of brevity we refrain from an extensive exposition on the use of the residual budget. Note, however, that this optimal use can be easily inferred from Propositions 4–8 below.

$\beta \in \left[\check{\beta}, 1\right]$. In these cases, the regulator has to compare the marginal gains associated with increased audit pressure on project classes where $\beta < \check{\beta}$ and $\beta > \check{\beta}$. That is, is it more efficient to add additional monitoring pressure to projects with lower or higher verifiability? Lower levels of β will be certainly monitored if

$$\frac{d\epsilon_{\check{\beta}}(0)}{d\alpha} > \frac{d\epsilon_1(\check{\alpha}(1))}{d\alpha}. \tag{19}$$

By use of condition (19), definition (17), and noting that $\check{\alpha}(1) = \check{\beta}$, we can derive the following proposition:

Proposition 4 *If $B > \int_{\check{\beta}}^{1} \check{\alpha}(\beta)\, n\, d\beta$ and*

$$\gamma > c_b''(0) \left[\frac{\theta'(\check{\beta})}{\check{\beta}\theta'(e^*)(c_g''(\check{\beta}) + \check{\beta} \cdot \theta''(\check{\beta}))} - \frac{1}{c_g''(0)} \right] \tag{20}$$

then $\beta_l < \check{\beta}$.

Proposition 4 establishes a sufficient condition for which, with the existence of a larger budget, it is optimal to use at least some of the resources to apply monitoring pressure to those projects with $\beta < \check{\beta}$. As stated in condition (20), this is the case if the probability of a b-type occurring is sufficiently large.

We now investigate a case where it might be efficient to, instead, increase auditing pressure for those projects where $\beta > \check{\beta}$. This is surely the case if inducing full compliance for all $\beta \geq \tilde{\beta}$ yields a higher marginal gain than starting to induce positive pressure, at levels $\beta < \check{\beta}$. Hence, a sufficient condition for increased monitoring at levels higher than $\check{\beta}$ is

$$\frac{d\epsilon_{\check{\beta}}(0)}{d\alpha} < \frac{d\epsilon_{\tilde{\beta}}(1)}{d\alpha}. \tag{21}$$

From (7) and (21), we can derive the following proposition:

Proposition 5 *If $\int_{\check{\beta}}^{1} \check{\alpha}(\beta)\, n\, d\beta < B \leq \int_{\check{\beta}}^{\tilde{\beta}} \check{\alpha}(\beta)\, n\, d\beta + \int_{\tilde{\beta}}^{1} \tilde{\alpha}(\beta)\, n\, d\beta$ and*

$$\gamma < c_b''(0) \left[\frac{p}{\check{\beta}c_g''(e_g^*)\theta'(e_g^*) + \tilde{\beta}\check{\beta}\theta'(e_g^*)\theta''(0)} - \frac{1}{c_g''(0)} \right] \tag{22}$$

then $\beta_l = \beta_m = \check{\beta}$.

Proposition 5 establishes sufficient conditions for which the regulator will refrain from monitoring projects with verifiability lower than $\check{\beta}$. This is obviously the case if the share of g-type projects is not too low. This is intuitive, as 'bad' types with $\beta \geq \check{\beta}$ are already in compliance. A low share of 'good' types would hence imply that the additional gains from increasing monitoring pressure on projects with high verifiability will be low.

Note, however, that for the budget range given in Proposition 5 it is not guaranteed that there exists a verifiability class for which g-type projects are in full compliance. Sufficient conditions for this being the case are established in the following proposition:

Proposition 6 *For a large enough budget B, there exists a $\beta_h > \beta_m$ where $z_g = e_g^*$ and $z_b = e_b^*$ for all $\beta \geq \beta_h$.*

(i) For $\beta_l < \beta_m$ threshold β_h exists if $\beta_h = f(\beta_l) \leq 1$ with $f(\beta_l) = \left(\pi c_b''(0) + (1-\pi)c_g''(0)\right) \frac{\theta'(e_g^*)\left(c_g''(e_g^*)\theta'(0) + p\,\theta''(0)\right)}{\pi\, c_b''(0)\, c_g''(0)\theta'(0)^2} \cdot \beta_l.$

(ii) For $\beta_l = \beta_m$, a sufficient condition for the existence of β_h is

$$B \geq \int_{\check{\beta}}^{\beta_0} \check{\alpha}(\beta)\, n\, d\beta + \int_{\beta_0}^{1} \tilde{\alpha}(\beta)\, n\, d\beta$$

for any β_0 for which $\check{\beta} < \beta_0 \leq \dfrac{\theta'(0)\left(c_g''(e_g(\check{\beta})) + \check{\beta}\theta''(e_g^* - e_g(\check{\beta}))\right)}{\theta'(e_g^* - e_g(\check{\beta}))\left(c_g''(e_g^*) + \tilde{\beta}\theta''(0)\right)}$

Proof See appendix. □

If the budget is large enough, the regulator is able to incentivize full compliance for all types with β larger or equal to the threshold level β_h. The budget level required for the existence of β_h is dependent on whether the regulator chooses to also put a positive monitoring pressure on classes of projects lower than $\check{\beta}$. If this is the case, it is possible via the comparison of slopes to express the level of β_h as a function of the threshold β_l, which is expressed in Proposition 6 (i). If $\beta_l = \check{\beta}$, a lower amount of budget is required for the existence of β_h. Sufficient conditions for the budget level required for the existence are given in Proposition 6 (ii).

Given that threshold classes $\hat{\beta}$, $\check{\beta}$, and $\tilde{\beta}$ can be derived from the individual optimization of project developers, a budget close enough to $\overline{B}$, automatically ensures the existence of all three thresholds—β_l, β_m, and β_h—within the optimal monitoring schedule. It remains to discuss the general features of the optimal monitoring schedule $(\alpha(\beta))_{\beta\in[0,1]}$ between those thresholds. For $\beta_l \neq \beta_m$, $\alpha(\beta)$ is increasing between both thresholds, as $\alpha(\beta_l) = 0$, while monitoring pressure for β close enough to β_m is strictly positive. Furthermore, for levels larger than β_h, optimal monitoring $\alpha(\beta)$ is strictly decreasing, as $\tilde{\alpha}(\beta)$ is decreasing in β, and no additional reduction in overreporting can be achieved by choosing $\alpha > \tilde{\alpha}(\beta)$.

The characteristics of optimal monitoring between β_m and β_h are less clear. On the one hand, we assume that—provided a large enough budget—all projects with $\beta \geq \check{\beta}$ will be monitored with at least probability $\check{\alpha}(\beta)$. Given that $\check{\alpha}(\beta)$ is decreasing in β, there exists a tendency for decreasing auditing pressure within $[\beta_m; \beta_h]$. Yet, there might exist also a tendency to increase auditing pressure for higher levels of β if $\frac{\partial^2\epsilon}{\partial\alpha\partial\beta} > 0$. Note, however, that this is surely not the case if $\frac{d\epsilon}{d\alpha}$ is strictly decreasing in β. An interesting case arises then if the budget is large enough for $\beta_h = \tilde{\beta}$, as $\check{\alpha}(\check{\beta}) = \tilde{\alpha}(\tilde{\beta}) = 1$. Hence, in this case if $\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta} < 0$ all project classes in $[\check{\beta}; \tilde{\beta}]$ will also be monitored with probability 1. We summarize this insight in the following proposition.

Proposition 7 *For a budget large enough to implement $\beta_h = \tilde{\beta}$ and if $\frac{\partial^2 (\epsilon)}{\partial\alpha\partial\beta} < 0$ in $[\beta_m, \beta_h]$, the regulator chooses $\alpha(\beta) = 1$ for $\beta \in [\beta_m, \beta_h]$.*

The explicit form of cross-derivative $\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta}$ in the range $[\beta_m, \beta_h]$ is obtained by taking the derivative of the middle term of (14) with respect to β, which yields

$$\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta} = \pi\theta'(x) \cdot \frac{c_g''(e(\alpha\beta))^2 - \alpha\beta\left(\alpha\beta\theta''(x)^2 + \theta'(x)\left(c_g'''(e(\alpha\beta)) - \alpha\beta\theta'''(x)\right)\right)}{\left(c_g''(e(\alpha\beta)) + \alpha\beta\theta''(x)\right)^3}, \tag{23}$$

where $x = e_g^* - e_g(\alpha\beta)$. Note that the cross-derivative might indeed be larger or smaller than zero, and could even switch signs over the range $[\beta_m, \beta_h]$. From (23), the sign depends on the structure of both $c(\cdot)$ and $\theta(\cdot)$. In particular, for relatively large $\theta''(x)$ and $\theta'''(x)$, the compliance incentive is larger than the deviation incentive and the cross-derivative is negative. That is, for a relatively 'stringent' ('lax') penalty policy, $\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta} < 0$ ($\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta} > 0$). Hence, Proposition 7 only applies if the penalty schedule is 'stringent', compared to abatement costs. Note, however, that the opposite case, relatively 'lax' penalties, is just as conceivable. For this case an interesting feature of optimal auditing in $[\beta_m, \beta_h]$ can be derived, which is summarized in Proposition 8.

Proposition 8 *For an existing β_h and $\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta} > 0$ in $[\check{\beta}, \beta_h]$, there exists a*

$$\beta_{min} = \frac{\theta'(0)\left(c_g''(e_g(\check{\beta})) + \check{\beta}\theta''(e_g^* - e_g(\check{\beta}))\right)}{\theta'(e_g^* - e_g(\check{\beta}))\left(c_g''(e_g^*) + \tilde{\beta}\theta''(0)\right)} \cdot \beta_h \tag{24}$$

for which the optimal monitoring pressure $\alpha(\beta)$ is decreasing in the interval $[\check{\beta}, \beta_{min}]$ and increasing in the interval $[\beta_{min}, \tilde{\beta}]$ if the budget is too small to allow for $\alpha(\beta) = 1$ within this range.

Proof See appendix. □

Somewhat counter-intuitively, it is feasible that for levels of β between $[\check{\beta}, \tilde{\beta}]$, optimal monitoring pressure is not always decreasing in β. In particular, it is possible that a 'U-shaped' monitoring pressure exists within the range $[\check{\beta}, \tilde{\beta}]$. The details of this behavior are shown formally in the mathematical appendix. As condition (18) is assumed to hold, the regulator will for all $\beta \geq \check{\beta}$ at least implement auditing pressure $\check{\alpha}(\beta)$ which is decreasing in β. Hence, for lower β in $[\check{\beta}, \beta_h]$, optimal monitoring is decreasing. Yet, if $\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta} > 0$, i.e. if penalties are 'lax', further increases in auditing pressure for larger β also yield larger gains from auditing. In fact, for higher levels of β the relative influence of monitoring α on the *expected* penalty is larger under a 'lax'

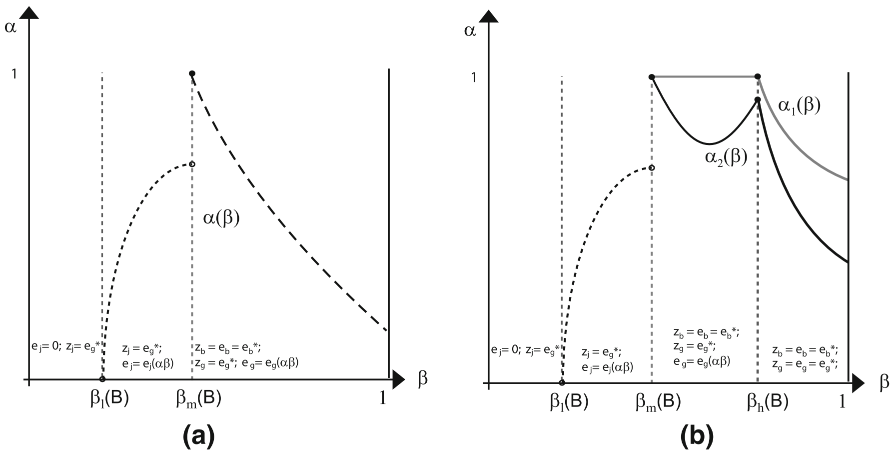

Fig. 2 Optimal monitoring with lower (case **a**) and larger (case **b**) monitoring budgets

penalty schedule than under a 'stringent' one. Hence, in the former case, it is optimal to further increase monitoring pressure as soon as β is large enough (i.e. larger than β_{min}).

Note, for the often-assumed quadratic forms of abatement cost and penalty functions, with constant second derivatives c'' and θ'', cross-derivative $\frac{\partial^2 \epsilon}{\partial\alpha\partial\beta}$ is positive (negative) iff

$$\alpha\beta < (>) \frac{c''}{\theta''}. \tag{25}$$

Hence, with quadratic functions, the general shape of optimal monitoring only depends on the relative convexities of abatement costs and the penalty schedule.

The findings established in Propositions 2–8 are represented in Fig. 2, which shows possible optimal monitoring strategies of a regulator with a limited budget. Begin by looking at Fig. 2a, depicting a case with a relatively narrow budget constraint. From Proposition 2, zero monitoring pressure will be applied for those projects with $\beta < \beta_l$. Furthermore, as the regulator applies auditing pressure $\check{\alpha}(\beta)$ for all projects where this is possible (Proposition 3) and $\check{\alpha}'(\beta) < 0$, there exists a β_m with $\alpha(\beta)$ decreasing in the range $[\beta_m; 1]$. Depending on the relative frequency of good- and bad-type projects, the left hand branch of the optimal monitoring schedule (i.e. for $\beta < \beta_m$) might either exist (Proposition 4) or not (Proposition 5).

Figure 2b represents cases for budgets large enough for β_h to exist (Proposition 6). In this case the left hand branch i.e. $\alpha(\beta)$ for $\beta < \beta_m$, is more likely to exist. Furthermore, for all depicted cases monitoring pressure decreases from β_h onwards, as with increasing verifiability β, lower levels of monitoring are required to induce full compliance of both types (i.e. $\tilde{\alpha}'(\beta) < 0$). The qualitative difference in monitoring in the depicted cases $\alpha_1(\beta)$, and $\alpha_2(\beta)$ are hence with respect to the optimal schedule in the range $[\beta_m; \beta_h]$. As laid out above, these cases are easiest to interpret if we assume penalty and cost functions to be quadratic.

Monitoring schedule $\alpha_1(\beta)$ represents the case of a larger budget with relatively strict monitoring (Proposition 7). Hence, in this case, projects with intermediate levels of verifiability are monitored with probability 1. With a comparatively 'lax' penalty scheme and an intermediate budget, optimal monitoring is 'U-shaped' between β_m and β_h, as established in Proposition 8. Given an intermediate budget, and the marginal gains of emissions reductions for a change in α are increasing in verifiability, an incentive exists to increase monitoring pressure in verifiability level from β_{min} to β_h. This case is represented by monitoring schedule $\alpha_2(\beta)$.

Note that provided a large enough budget, the above depicted optimal monitoring strategy will generally lead to a mixed equilibrium with respect to separation of cost types. For budgets large enough to ensure the existence of β_m, there will be pooling of cost types situated below that threshold, and full separation otherwise. This is due to the fact that a bad-type project will only mimic a good-type project if the corresponding auditing pressure is $\alpha(\beta) < \check{\alpha}(\beta)$. For all cases where $\alpha(\beta) \geq \check{\alpha}(\beta)$, bad-type projects will truthfully report $z_b = e_b^*$, there is hence full separation of types.[19]

4 Regulation with project admission

The existence of the different thresholds identified above suggests an interesting extension of the regulator's set of instruments to reduce overreporting within credit-based mechanisms. In addition to monitoring, the regulator could exclude project types with low levels of verifiability from the mechanism. Within the CDM for example, the regulator can refuse the admission of a project if the Project Design Document or the proposed Baseline Method do not correspond to the specified standards.[20] It is hence quite plausible that project admission standards could also include a minimum level of verifiability.

The above-presented model results can be used to gain valuable insights for determining sensible cut-off levels for project admission. In the context of this model, the regulator would have to decide on a maximum tolerable level of opportunistic misreporting given a specified budget. In most theoretical contributions on incomplete enforcement of environmental policy instruments, the regulator is assumed to minimize emissions in the regulated system. As far as climate change is concerned, this definition of the regulator's objective seems sensible. In light of the fact that there exists no consensus on the allocatively optimal level of emission reductions, determining a specific cut-off level based on welfare considerations would be particularly problematic. As long as the exact level of the social cost of carbon is still disputed, the optimal regulation under incomplete enforcement remains just as undetermined as the optimal level of abatement.

[19] Note that given that the regulator's choice is limited to auditing pressure α—which is to be applied before the cost type is known—there exist no additional devices to induce further separation of types for projects with $\beta \in [0; \beta_m]$. In principle, an additional increase in the wedge between the expected payoffs of both types could be obtained by conditioning penalty $\theta(x)$ on the cost type. However, such an increase in the penalty for (discovered) bad types would only lead to a shift of the thresholds $\beta_l(B)$ and $\beta_m(B)$ to the left, while all our qualitative results would continue to hold.

[20] The probability of rejection for a submitted CDM project is about 5 percent (UNEP/Risoe 2010).

Yet, the CDM remains a matter of political dispute. Even in the potential buyer countries, the use of Certified Emission Reductions for meeting the Kyoto targets is not undisputed, as some observers still challenge the morality of reducing emissions in third-world countries. As a consequence, the sudden discovery of large scale fraud within a CDM project would significantly undermine the credibility of the whole Kyoto emissions trading regime as an instrument to achieve emission reductions. Hence, it is plausible that the architects of the mechanism might want to minimize the risk of discovery of fraud by reducing the range of eligible projects. The objective of minimizing emissions within the combined markets would then imply a 'no-tolerance' constraint, excluding any amount of overreporting within the credit-based system. In the framework presented above, such a policy would exclude all projects with a verifiability lower than the minimum implementable $\beta_h(B)$. In this case all projects would be in perfect compliance.

A 'no-tolerance' policy would result if program (6) were optimized simultaneously over $\alpha(\beta)$ and project admission cut-off level $\beta_h(B)$. Obviously, with a large enough budget, i.e. $B \geq \check{B} = \int_{\tilde{\beta}}^{1} \tilde{\alpha}(\beta) d\beta$, the regulator would simply restrict the set of eligible projects to the ones for which $\beta \geq \tilde{\beta}$ and monitor these projects with the corresponding pressure of $\tilde{\alpha}(\beta)$. For those cases where $B < \check{B}$, the corresponding cut-off value would have to be higher, as the monitoring budget constraint becomes binding. As a consequence, the amount of eligible projects is further restricted. Note that for such a regime, the regulator's monitoring schedule will not be subject to an actual optimization, as for each class of β the optimal monitoring policy is already known to be $\tilde{\alpha}(\beta)$. Hence, the regulator's decision is reduced to determining the cut-off level for project admission β_h for which

$$B = \int_{\beta_h}^{1} \tilde{\alpha}(\beta)\, n\, d\beta. \tag{26}$$

Another intuitively sensible cut off-level would be $\beta_m(B)$, implying that overreporting is only deterred for less efficient projects, while some amount of 'shirking', in the reduction of more efficient projects, would still be possible. This less restrictive cut-off level might be acceptable if the regulator also had to guarantee a large enough market volume for the credit-based regime.

The above-made considerations could also be extended to take into account that incomplete enforcement can also exist on the associated cap-and-trade market, as in Sigman and Chang (2011). In this case, the amount of overreporting allowed within the credit-based regime might be adjusted to the corresponding share of non-compliance within the cap-and-trade market. This would require a combined model of both markets, which represents an interesting extension for future research.

5 Conclusion

The model presented within this paper allows some interesting insights into the nature of optimal monitoring for credit-based systems, like the Clean Development Mechanism. It was shown that under these circumstances even with an unlimited monitoring budget, overreporting of reductions can not be completely disincentivized. The more interesting and realistic results are, however, achieved when the regulator is assumed to be constrained in both its budget and the information it holds on regulated emitters.

While under an unlimited budget all projects with positive verifiability will be monitored, the situation significantly changes under the assumption of a budget constraint. For this case, it is shown that a rational regulator will completely refrain from monitoring those projects that are most difficult to verify. For the range of verifiability for which all projects are in full compliance, optimal monitoring decreases in verifiability. Both results are in line with the findings by Macho-Stadler and Perez-Castrillo (2006) who analyze incomplete enforcement of emission taxes without asymmetric information on costs. However, unlike emission taxes, the general principle of credit-based emission trading systems implies that the regulator cannot refrain to simply maximize the *actual* emission reductions but needs also to reduce the level of overstatement within the projects' *reported* reductions. This is due to the fact that certificates issued on the basis of the reports will be used to offset actual emissions elsewhere. Hence, contrary to the the tax case, the regulator needs to minimize the *overall* level of overreporting.

Due to differences in the objective function of the regulator as well as the asymmetric information on cost types, the optimal monitoring strategy derived above significantly differs from those proposed in the context of emission taxes or a cap-and-trade system. First, with a large enough share of projects with high abatement costs, the regulator has an incentive to induce full compliance for these cost types over the whole range of verifiability where this is possible. Second, with decreasing verifiability, the optimal audit pressure features a 'jump' downwards when reaching levels of verifiability, for which the regulator cannot deter overreporting by high-cost projects. Third, for projects with intermediate verifiability, optimal monitoring pressure can be either non-increasing or 'U-shaped', depending on the relative stringency of the penalty schedule.

As the importance of credit-based mechanisms grows, attention is turning to the optimal implementation and regulation of such schemes: something this paper has attempted to address. Interesting avenues for further investigation include the introduction of uncertainty over costs and plausible reduction levels, the analysis of combined asymmetric information problems within cap-and-trade and credit schemes, as well as further optimal project admission ('cut-off') policies.

Mathematical appendix

Proof of Proposition 2:

For $\beta \to 0$, $\frac{d\epsilon_\beta}{d\alpha}$, given by equation (14), approaches 0 as well, as the bracketed term in the first line is never infinitely large for $e \in [0, e_g^*]$. Hence, according to condition (12), for $\beta_1 < \beta_2$, reducing α_1 to 0 is always efficient for β_1 small enough. Furthermore, it is easy to check that for $\alpha = 0$ the the bracketed term in the first line of (14) is increasing in β. Hence, it follows from condition (12) that all projects with $\beta > \beta_l(B)$ are monitored with positive probability. □

Proof of Proposition 6:

(i) If $\beta_l < \beta_m$ it follows from (12) that β_h only exists if

$$\frac{\partial \epsilon_{\beta_h}(\tilde{\alpha}(\beta_h))}{\partial \alpha} = \frac{\partial \epsilon_{\beta_l}(0)}{\partial \alpha}. \tag{27}$$

After substitution of (14) into (27) for the respective values and rearranging, β_h can be expressed as $\beta_h = f(\beta_l)$, where $f(\beta_l)$ is defined as in Proposition 6 i). Hence, as $\beta \in [0; 1]$, β_h exists if $f(\beta_l) \leq 1$.

(ii) If $\beta_l = \beta_m$ it follows from (12) that for the existence of the largest possible β_h, i.e. $\beta_h = 1$, the budget is at least to be large enough to allow for some $\beta_y \geq \check{\beta}$ the equalization of slopes as follows

$$\frac{\partial \epsilon_1(\tilde{\alpha}(1))}{\partial \alpha} = \frac{\partial \epsilon_{\beta_y}(\check{\alpha}(\beta_y))}{\partial \alpha}. \tag{28}$$

Noticing that $\tilde{\alpha}(1) = \tilde{\beta}$ and $\check{\alpha}(\beta_y) = \check{\beta}$, substituting (14) into (28) and solving for β_y yields

$$\beta_y = \frac{\theta'(0)\left(c_g''(e_g(\check{\beta})) + \check{\beta}\theta''(e_g^* - e_g(\check{\beta}))\right)}{\theta'(e_g^* - e_g(\check{\beta}))\left(c_g''(e_g^*) + \tilde{\beta}\theta''(0)\right)} \tag{29}$$

the upper boundary of β_0 in Proposition 6 ii). Hence, if the budget level is high enough to apply monitoring pressure $\tilde{\alpha}(\beta)$ for all $\beta \geq \beta_0$, β_h will necessarily exist. □

Proof of Proposition 8:

Note that if β_h exists, $\beta_m = \check{\beta}$, as (18) is assumed to hold. For an existing β_h, condition (12) requires that any $\beta_0 > \check{\beta}$ will be monitored with $\check{\alpha}(\beta_0)$ if

$$\frac{\partial \epsilon_{\beta_h}(\tilde{\alpha}(\beta_h))}{\partial \alpha} \geq \frac{\partial \epsilon_{\beta_0}(\check{\alpha}(\beta_0))}{\partial \alpha}, \tag{30}$$

For condition (30) holding with equality, $\beta_0 = \beta_{min}$, as defined in Proposition 8. Note that $\beta_{min} > \check{\beta}$ if

$$\beta_h \cdot \frac{\theta'(0)}{c_g''(e_g^*) + \tilde{\beta}\theta''(0)} > \check{\beta} \cdot \frac{\theta'(e_g^* - e_g(\check{\beta}))}{c_g''(e_g(\check{\beta})) + \check{\beta}\theta''(e_g^* - e_g(\check{\beta}))} \Longleftrightarrow \frac{\partial \epsilon_{\beta_h}(\tilde{\alpha}(\beta_h))}{\partial \alpha}$$
$$> \frac{\partial \epsilon_{\check{\beta}}(\check{\alpha}(\check{\beta}))}{\partial \alpha}, \tag{31}$$

which is always the case for $\frac{\partial^2\epsilon}{\partial\alpha\partial\beta}$. As $\check{\alpha}(\beta)$ is strictly decreasing in β optimal monitoring $\alpha(\beta)$ is also decreasing in the range $[\check{\beta}; \beta_{min}]$.

It remains to show that $\alpha(\beta)$ is increasing in β within the range $[\beta_{min}; \beta_h]$. First, note that condition (12) requires

$$\frac{\partial\epsilon_{\beta_h}(\tilde{\alpha}(\beta_h))}{\partial\alpha} = \frac{\partial\epsilon_{\beta_0}(\check{\alpha}(\beta_0))}{\partial\alpha}, \tag{32}$$

for any $\beta_0 \in [\beta_{min}; \beta_h]$. Note further that

$$\begin{aligned}\frac{d^2\epsilon}{d^2\alpha}\\ = \frac{\pi\beta^2\theta'(x)\left(-2c_g''(e_g(\alpha\beta))\theta''(x) - 2\alpha\beta\theta''(x)^2 + \theta'(x)\left(-c_g'''(e_g(\alpha\beta)) + \alpha\beta\theta'''(x)\right)\right)}{\left(c_g''(e_g(\alpha\beta)) + \alpha\beta\theta''(x)\right)^3},\end{aligned} \tag{33}$$

where $x = e_g^* - e_g(\alpha\beta)$. Through comparison of enumerators of (23) and (33) it is easy to see that if $\frac{\partial^2\epsilon}{\partial\alpha\partial\beta} > 0$ then $\frac{d^2\epsilon}{d^2\alpha} < 0$. Hence, condition (32) can only hold if $\alpha(\beta)$ is increasing over the range $[\beta_{min}; \beta_h]$. □

Acknowledgements The authors are grateful to two anonymous reviewers, the Editor, and participants of WCERE 2010 for helpful comments and suggestions that improved earlier versions of this paper.

References

Cohen, M. A. (1999). *Monitoring and enforcement of environmental policy, International yearbook of environmental and resource economics* (Vol. III). Cheltenham: Edward Elgar.

Cremer, H., & Gahvari, F. (2002). Imperfect observability of emissions and second-best emission and output taxes. *Journal of Public Economics, 85*(3), 385–407.

Harford, J. D. (1978). Firm behavior under imperfectly enforceable pollution standards and taxes. *Journal of Environmental Economics and Management, 5*(1), 26–43.

Harford, J. D. (1987). Self-reporting of pollution and the firm's behavior under imperfectly enforceable regulations. *Journal of Environmental Economics and Management, 14*(3), 293–303.

Heyes, A. (2000). Implementing environmental regulation: Enforcement and compliance. *Journal of Regulatory Economics, 17*, 107–129.

Heyes, A. G. (1994). Environmental enforcement when inspectability is endogenous: A model with overshooting properties. *Environmental and Resource Economics 4*, 479–494.

Heyes, A., & Kapur, S. (2011). Regulatory attitudes and environmental innovation in a model combining internal and external R&D. *Journal of Environmental Economics and Management, 61*(3), 327–340.

Keeler, A. G. (1991). Noncompliant firms in transferable discharge permit markets: Some extensions. *Journal of Environmental Economics and Management, 21*(2), 180–189.

Macho-Stadler, I. (2006). *Environmental regulation: Choice of instruments under imperfect compliance*. UFAE and IAE working papers. Unitat de Fonaments de l'Analisi Economica (UAB) and Institut d'Analisi Economica (CSIC).

Macho-Stadler, I., & Perez-Castrillo, D. (2006). Optimal enforcement policy and firms' emissions and compliance with environmental taxes. *Journal of Environmental Economics and Management, 51*(1), 110–131.

Malik, A. S. (1990). Markets for pollution control when firms are noncompliant. *Journal of Environmental Economics and Management, 18*(2), 97–106.

Ohndorf, M. (2010). *Optimal monitoring for project-based emissions trading systems under incomplete enforcement*. IED working paper 13. Institute for Environmental Decisions, ETH Zurich, Zurich.

Okubo, Y., Hayashi, D., & Michaelowa, A. (2011). NAMA crediting: How to assess offsets from and additionality of policy-based mitigation actions in developing countries. *Greenhouse Gas Measurement and Management, 1*, 37–46.

Sandmo, A. (2002). Efficient environmental policy with imperfect compliance. *Environmental and Resource Economics, 23*, 85–103.

Schmutzler, A., & Goulder, L. H. (1997). The choice between emission taxes and output taxes under imperfect monitoring. *Journal of Environmental Economics and Management, 32*(1), 51–64.

Sigman, H., & Chang, H. F. (2011). The effect of allowing pollution offsets with imperfect enforcement. *American Economic Review, 101*, 268–272.

Stranlund, J. K. (2007). The regulatory choice of noncompliance in emissions trading programs. *Environmental and Resource Economics, 38*, 99–117.

Stranlund, J. K., & Chavez, C. A. (2000). Effective enforcement of a transferable emissions permit system with a self-reporting requirement. *Journal of Regulatory Economics, 18*(2), 113–131.

Stranlund, J. K., Costello, C., & Chavez, C. A. (2005). Enforcing emissions trading when emissions permits are bankable. *Journal of Regulatory Economics, 28*, 181–204.

UNEP/Risoe. (2010). *UNEP Risoe CDM/JI pipeline analysis and database, June 1st 2010. Database and analysis tool*. United Nations Environment Programme, RISOE Centre, Denmark. http://cdmpipeline.org/.

UNFCCC. (2002). *Report of the 7th conference of the parties of the parties to the Kyoto Protocol, Marrakech*, *UNFCCC/CP/2001/13*. United Nations Framework Convention Climate Change, Published 21 January 2002.

Wara, M. (2007). Is the global carbon market working? *Nature, 445*, 595–596.

Wara, M. (2008). Measuring the clean development mechanism's performance and potential. *UCLA Law Review, 55*(6), 1759–1803.

WorldBank. (2011). *State and trends of the carbon market 2011*. Washington, DC.