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Abstract

The problem addressed in this work is concerned with an important challenge faced by any green aware global company to keep its emissions within a prescribed cap. The specific problem is to allocate carbon reductions to its different divisions and supply chain partners in achieving a required target of reductions in its carbon reduction program. The problem becomes a challenging one since the divisions and supply chain partners, being autonomous, could exhibit strategic behavior. We model strategic behavior of the divisions and partners using a game theoretic approach leading to a mechanism design approach to solve this problem. While designing a mechanism for the emission reduction allocation problem, the key properties that need to be satisfied are dominant strategy incentive compatibility (DSIC), strict budget balance (SBB), and allocative efficiency (AE). Mechanism design theory has shown that it is not possible to achieve the above three properties simultaneously. We propose two solutions to the problem satisfying DSIC and AE: (1) a reverse auction protocol and (2) a forward auction protocol, while striving to keep the budget imbalance as low as possible. We compare the performance of the two protocols using a stylized, representative case study.

Keywords (separated by '-')

Carbon emission reduction - Emission cap - Emission reduction allocation - Mechanism design - Incentive compatibility - Allocative efficiency - Budget imbalance - Vickrey-Clarke-Groves mechanism - Redistribution mechanisms

Mechanism Design for Allocation of Carbon Emission Reduction Units: A Study of Global Companies with Strategic Divisions and Partners

Deepak Bagchi, L. Udaya Lakshmi, Y. Narahari, Shantanu Biswas, P. Suresh, S.V. Subrahmanya, and N. Viswanadham

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1 Introduction

The impact of global warming and climate change is one of the most seriously talked about issues in recent times. The global warming and climate change phenomenon have been associated with the accumulation of greenhouse gases (GHG) in the atmosphere. Some atmospheric gases, mainly carbon dioxide (CO_2), methane (CH_4), halo carbons (HFCs and PFCs), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6), are called greenhouse gases (GHG). These gases act as a natural blanket retaining the Earth's heat. Among these gases, CO_2 is found to have the maximum effect; hence, GHG emissions are often referred to as carbon emissions. Global economic growth and the surge in industrial activities have increased the accumulation of these gases over a period of time. The emissions are measured in terms of carbon credits where one carbon credit is equivalent to one metric tonne of CO_2 emitted. All other GHGs are converted into carbon equivalent by using standard conversion metrics (UNFCCC 2009).

As the effect of global warming and climate change is significant, countries around the world have started putting in efforts towards finding a solution to mitigate the GHG emissions. One such effort is the *cap and trade* scheme. A cap and trade system allows corporations or national governments to trade emission allowances under an overall cap, or limit, on their emissions. This mechanism involves two parties, the governing body and the regulated entities that emit pollution. The governing body allocates a limit on the total amount of emissions that could be emitted in a given period, called as *cap,* and would issue rights, or allowances, corresponding to that level of emissions. Regulated entities would be required to hold equal or more allowances than their cap for their emissions. Normally the cap on a regulated body is less than the current emissions emitted by it. A cap on emissions limits the total amount of allowable emissions, and it can be lowered to achieve stricter environmental standards.

Let us consider a global company (refer to Fig. 1) that gets a cap on its overall emissions. This cap could be prescribed by a regulatory authority or by any other regulatory process. To honor the cap, the company will be required to reduce its

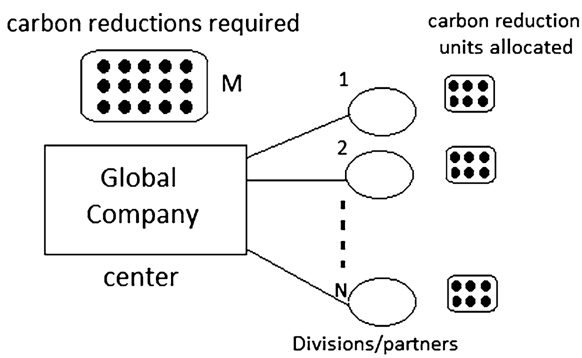

Fig. 1 Allocation of carbon emission reductions among divisions

GHG emissions. As an example, suppose the company currently emits x units of GHG and the company has been stipulated a cap of y emission units. The company is then required to reduce $m = x - y$ emission units (called emission reduction units).

In order to accomplish this, the company would look at its divisions and supply chain partners to help reduce emissions by the required amount. The effort of emission reduction involves cost which could vary among the divisions and partners. We will use the phrase *emitting agents* to describe the divisions and partners involved. Some emitting agents will incur higher costs than others in the task of achieving a certain amount of emission reduction. The challenge for the global company will be to allocate the required number of reductions in a fair manner among the emitting agents, such that the total cost of reduction is minimized. Since the emitting agents are often autonomous entities and could exhibit strategic behavior, the company may not be able to elicit the emission reduction cost curves from the individual emitting agents truthfully. So we invoke techniques from game theory and mechanism design to elicit the cost curves truthfully and then allocate the emission reduction units.

1.1 Examples of Cap and Trade Scheme

We provide two motivating examples in global settings where the research reported in this work are relevant.

1.1.1 Allocation Under the European Union Emission Trading Scheme (EU ETS)

The European Union has shown leadership in this initiative and was one of the early signatories to the Kyoto protocol. A large number of companies in the region have claimed to have adhered to the caps or have offset their extra emissions through credits generated by Clean Development Mechanism (Kyoto protocol). The big worrying factor is that several major polluting industries have not only met their caps but have saved huge amounts of certified emission reduction units. Several campaigners have argued that the system followed by the European Union is flawed and has failed in its fundamental aim to reduce emissions (Ellerman and Joskow 2008). So instead of providing a mechanism for industries to reduce emissions, it has in fact created intangible wealth for many industries. This has totally invented a $126 billion market and has the potential to flare into a $2 trillion green giant over the decade.

1.1.2 Oil and Gas Industry

Industries in this business generally are very large having global presence and financially very strong. They are also among the biggest sources of emissions. Some of the major companies in the segment like British Petroleum (BP), Amoco, and Shell have adopted best practices in achieving sustainability. Sustainable development here refers to development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations General Assembly Report 1987). They have consciously made efforts to reduce their emission levels without losing on the natural growth curve. These three companies have practiced cap and trade mechanism among its units and have reported some interesting positive effects, including the claim of meeting their emission reduction targets within 2 years, on their emission reduction program. We give the case of BP (Akhurst et al. 2003) as a motivating example for the proposed mechanism design approach.

BP is one of the largest corporate in oil and gas. It has operations spread across every aspect of fossil fuels, right from exploration and refining to retail and trading. It also has business in renewable energy like biofuels, solar, and wind. It has operations in more than 80 countries and also has significant carbon footprint across the globe. In the year 2000, BP strategically re-branded itself as "Beyond Petroleum" and set about reducing carbon footprint to 10% less than its emission level in 1990. In the year 2001, BP declared itself a carbon neutral company. Carbon neutral means to have a net zero carbon emission, that is, the total amount of carbon released has been offset either by improving the process or by buying enough carbon credits. BP deployed a cap and trade mechanism among its business units to achieve this (Akhurst et al. 2003). BP has about 150 business units (BUs); a central Integrated Supply and Trading (IST) group was set up to enforce and monitor the cap and trade mechanism among all its business units. To set the ball rolling, each of the 150 BUs was handed out a fixed number of annual allowances (CAP) to emit GHG. Each BU was expected to check and keep its emission levels under the permitted cap. However, they were allowed to trade their allowances among other units throughout the year. At the end of the year, any BU exceeding its cap was allowed to buy offset credits from the external market. BP at an organizational level also decided the cap as 10% less than their total GHG emission level in 1990, and this cap was used as a central link between the cap allocation among the units and the target set out by BP. The aggregate allowances available to individual units were determined using the group cap set by BP.

2 The Problem and Relevant Work

2.1 Emission Reduction Allocation Problem

We consider a global company or a large-scale industry that has several independent emitting agents supporting the business of the industry. These emitting agents could be the different divisions of the company and also its supply chain partners. Let us assume that the company has a total of n such agents. The emission reduction process incurs cost, and the cost of per unit of reduction varies among the agents. The motivation for undertaking the mandate to reduce the emissions can be interpreted in the following ways:

- The industry has been mandated a carbon cap by a regulatory authority and the company has to honor this cap by achieving the required quantum of reductions.
- The industry undertakes the emission reduction initiative under corporate social responsibility initiative. Hence, rather than buying the emission reduction units from third party carbon markets, the industry wants to make best use of its internal divisions and partners for this initiative.
- The industry considers the emission reduction initiative as a part of their branding activities. This could be a factor in attracting prospective clients who focus on emission neutral solutions.
- The industry wishes to reduce its emission footprints, but the solution of buying emission reduction units from an outside carbon market may be higher than the cost that the industry incurs through an internal drive.
- The industry by undertaking its own emission reduction initiatives will be better off achieving sustainability.

Based on above observations, we can say that all the emitting agents will be motivated to be a part of this initiative, and further, no players will be worse off by participating in this initiative. We assume that all players are intelligent and have the capability to compute their own emission levels and have an accurate knowledge of cost curves for reducing emissions. The cost curves are private information of emitting agents.

For the purposes of this work, we assume that the cost curve of each agent is a marginally increasing piecewise constant cost curve as shown in Fig. 2. This is a reasonable assumption to make since the marginal cost typically increases with the quantum of emission reduction required. A realistic assumption to make is that each agent has an upper bound on the number of emission reductions possible.

A typical cost curve as described above can be generally given by a sequence of tuples $<p, u, c>$, where p denotes the agent, u is the number of emission units that can be reduced by p at a cost c. The tuples for agent i are given as $<i, u_{i1}, c_{i1}>$, $<i, u_{i2}, c_{i2}>$, …, $<i, u_{it}, \infty>$, where t is the number of tuples in the type of agent i (Arava et al. 2010b). Tεe here shows that the unit cannot reduce more than $u_{i(t-1)}$ number of reductions. Here, c_{ik} is the cost of per unit of reduction for the range $[u_{i(k-1)}+1, u_{ik}]$. For the first tuple for player i, the cost is for $[1, u_{i1}]$. Also, we have $u_{i1} < u_{i2} < \ldots < u_{it}$ and $c_{i1} < c_{i2} < \ldots < c_{it}$ (refer to Fig. 2).

The cost for x units of emission reductions by player i is given by Eq. 1.

$$\mathrm{cost}_i(x) = \begin{cases} I\mathrm{Cost} + S\mathrm{Cost} & \text{if } x > 0 \quad (1) \\ 0 \text{ otherwise} & \quad (2) \end{cases}$$

where

$$I\mathrm{Cost} = \begin{cases} u_{i1} \times c_{i1} & \text{if } x \geq u_{i1} \\ x \times c_{i1} & \text{otherwise} \end{cases}$$

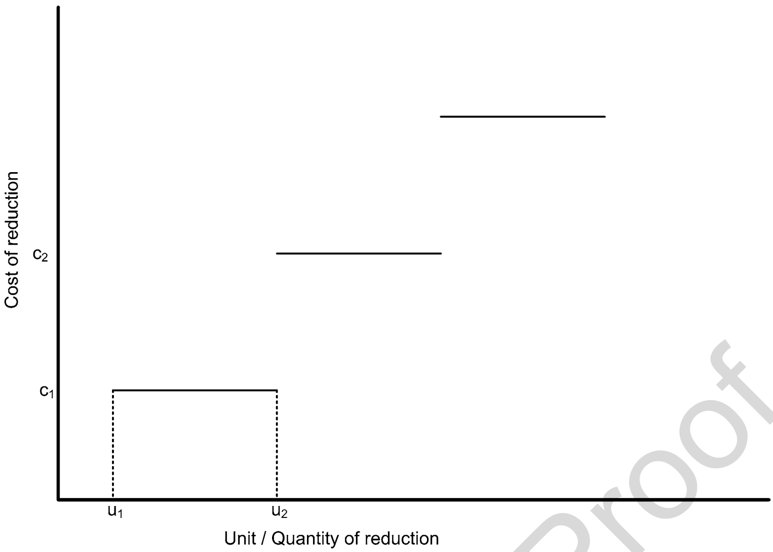

Fig. 2 Cost curves for different agents representing carbon reduction costs

and

$$S\text{Cost} = \begin{cases} \left[x - \left[\sum_{k=1}^{n} (u_{i(k+1)} - u_{ik}) \right] \right] \times c_{i(n+1)} + \sum_{k=1}^{n-1} \left[(u_{i(k+1)} - u_{ik}) * c_{i(k+1)} \right] & \text{if } x > u_{i1} \\ 0 \text{ otherwise} & \end{cases}$$

To obtain n, we have to proceed as long as $\left[\sum_{k=1}^{n} (u_{i(k+1)} - u_{ik}) \right]$, that is, the summation of the number of reductions is less than or equal to x. When $x > u_{i1}$, ICost denotes the cost of first u_{i1} reductions and SCost denotes the cost of the rest $x - u_{i1}$ reductions. [AU2]

Example: Suppose the bid by player A is <A, 25, 50>, <A, 50, 100>, <A, 75, 125>, <A, 100, ∞>. The cost of 75 units of reduction by player A is 6,875.

The global company or industry in question could be regarded as a social planner having the objective of achieving maximum possible reduction through emitting agents at minimum cost. Let m denote the number of emission units the industry wishes to reduce. The problem is to allocate these m units to n players. In order to allocate the emission reduction units efficiently among its divisions, the company uses the cost curves reported by the agents. Mathematically, this can be described by Eq. 3.

$$\text{Minimize} \sum_{i} \sum_{j} (u_{ij} - u_{i(j-1)}) p_{ij} \tag{3}$$

$$\text{subject to} \sum_{i}\sum_{j}(u_{ij} - u_{i(j-1)}) \geq m$$

i=1,…,n and j=1,…,t

Another scenario could be where the global company initially fixes a budget b to be used for the emission reduction initiative and seeks to find the maximum value of m that can be achieved from the players. This formulation is given in Eq. 4.

$$\text{maximize } m \text{ s.t. } t\text{cost} \leq b \tag{4}$$

$t$cost is the total cost for achieving a reduction of m units.

2.2 Related Work

In our work, we focus on using game theory and mechanism design to address the problem of effectively allocating emission reduction units to different emitting agents. For the extensive treatment of game theory and mechanism design with applications, refer to Mas-Collel et al. (1995) and Narahari et al. (2009). The carbon reduction unit allocation has been done in the past using auction or grandfathering or load-based allocations (LBA) method (United Nations Industrial Development Organization Report 2007). Among these methods, the grandfathering approach is quite popular. However, an issue with the grandfathering method is that the cap allotted to a polluter is higher in case the polluter has a history of emitting higher levels of carbon.

[AU3] Baliga and Maskin (2003) survey the concepts of the theory of mechanism design in the context of environment pollution. They consider the pollution to be an example of economic activities that goes uncharged. Further they have shown that any Pareto-efficient agreement involving two or more communities is vulnerable to free riding. So, it is required that the government has to impose a Pareto-efficient vector of quotas (q_1, …, q_N), where for each j, community j is required to reduce pollution by at least the amount q_j. Further they say that the government has to set a vector of subsidies (s_1, …, s_N), where for each j, community j is paid s_j for each unit of reduction it does. These solutions are studied in two information environments (preference profile is verifiable by the government (complete information) and not verifiable (incomplete information)). However, they have assumed that the cost of per unit of emission reduction is unity.

Dutta and Radner (2000, 2006) model the problem of climate change as a dynamic game between the countries around the globe. The model of the game proposed is strategic, justifying the rational decision processes around the globe. They use noncooperative game theoretic approach in analysis, which may be seen as more realistic than the cooperative counterpart. Three aspects of the problem [AU4] have been analyzed in these papers: Global Pareto Optimum (GPO) paradigm in which each player looks towards identifying the emission profile over the game which maximizes the global welfare, Business as Usual (BAU) model in which each player chooses emission vector leading to maximization of the respective individual welfare, and BAU reversion threat model considers situation where players play according to an agreed-upon norm. The equilibrium vector of this model is sandwiched between GPO and BAU vectors. The model is fairly simple, but the main result only shows that BAU scenario will definitely lead to poor results compared to the global welfare scenario.

The paper by Arava et al. (2010a) introduces carbon economic issues in the world today and carbon economic problems facing global industries. The paper identifies four problems faced by global industries: carbon credit allocation (CCA), carbon credit buying (CCB), carbon credit selling (CCS), and carbon credit exchange (CCE). Further, the paper argues that these problems are best addressed as mechanism design problems and describes in detail the carbon credit allocation problem. Another paper by Arava et al. (2010b) further explores the carbon credit allocation problem for a global industry that wants to reduce their own carbon footprints. The paper assumes that the industry has multiple divisions which have their own cost curves for emission reduction and develops a mechanism to allocate the total emission reduction units to the divisions such that the total cost of reducing the emission is minimum. Both of these papers have an appropriate model for the carbon reduction allocation within an organization, but the approach assumes the players are not strategic.

2.3 Contributions

The specific problem we address in this work is that of a global company (or in general a social planner) allocating carbon emission reductions to its different divisions and supply chain partners towards achieving a required target of carbon reduction units at minimum cost. There is very little extant literature on this problem, and to the best of our knowledge, this problem has been addressed in the literature under a simplified assumption that the divisions and partners are honest and do not indulge in strategic interactions. This assumption is not credible in a real-world setting since the divisions and partners are autonomous entities and may not be willing to reveal private information such as emission reduction cost curves. We explicitly address the issue of strategic nature of players using mechanism design.

- We first justify the use of mechanism design for this problem and identify important properties to be satisfied by any solution to the problem. We focus on three important properties: dominant strategy incentive compatibility (DSIC) (truthfulness), allocative efficiency (AE), and budget balance (BB). The classical Vickrey-Clarke-Groves (VCG) mechanisms satisfy DSIC and AE but do not satisfy BB, so we propose the use of redistribution mechanisms which reduce the budget imbalance while preserving DSIC and AE (due to an impossibility result in mechanism design, DSIC, AE, and BB can never be simultaneously achieved).
- We then set up a reverse auction protocol where the global company (or social planner) procures emission reductions from divisions and partners using an extension of the redistribution mechanisms proposed by Cavallo (2006). To reduce the budget imbalance further, we propose an innovative forward auction

protocol which achieves fewer imbalances when compared to the reverse auction protocol under realistic conditions. Moreover, the forward auction protocol has the appealing characteristic of amply rewarding divisions which reduce the emissions and appropriately penalizing divisions which do not participate in emission reductions.

- We present a detailed case study of a global company with five strategically acting divisions and experiment with the reverse auction protocol and forward auction protocol under three representative scenarios to illustrate the efficacy of the proposed mechanisms.

We believe the mechanisms developed in this work will be a key ingredient of the carbon footprint reduction program of any global company. The results can be applied to any central agency which needs to allocate emission reductions to a set of strategic emitting agents.

3 A Mechanism Design Approach to Emission Reduction Allocation

3.1 Relevance of Mechanism Design to the Problem

The emission reduction allocation problem described above is essentially a decision or optimization problem with incomplete information. More specifically, we have the following characteristics:

- There is a set of players who interact in a strategic way. The players have well-defined payoff functions. They are rational in the sense of striving to maximize their individual payoffs. The objectives of the individual players could be conflicting.
- Each player holds certain information which is private (e.g., cost curves) and only this player would know it deterministically; other players do not know this information deterministically. Thus, the situation is one of incomplete and decentralized information. There is also certain other information which all players know and all players know that all players know and so on. Such information is common knowledge.
- Each player has a choice of certain strategies that are available to them. The players have enough intelligence to determine their best response strategies.

A natural way of modeling problems with the above characteristics is through game theory. In all the cases, it is required to implement a system-wide solution that will satisfy certain desirable properties. In order to do this, an elegant way is to induce a game among the players in such a way that, in equilibrium of the induced game, the desired system-wide solution is implemented. Mechanism design provides the process for such reverse engineering of games. In general, *mechanism design* is concerned with settings where a social planner (global company in this case) faces the problem of aggregating the *announced preferences* of multiple agents into a collective (or social) decision when the *actual preferences* are not publicly known. The collective decisions are described by the so-called social choice function. The mechanism design problem is to come up with a mechanism that implements a *desirable* social choice function. Some desirable properties which are sought from a social choice function and hence from the implementing mechanism (and, in the present case, from carbon reduction allocations) are described below (Mas-Collel et al. 1995; Narahari et al. 2009).

3.1.1 Solution Equilibrium

The solution of a mechanism is in equilibrium, if no agent wishes to change its bid, given the information it has about other agents. Many types of equilibria can be computed given the assumptions about the preferences of agents (buyers and sellers), rationality, and information availability. They include *Nash equilibrium*, *Bayesian Nash Equilibrium*, and *weakly dominant strategy equilibrium*. It has been shown that weakly dominant strategy equilibrium is a special case of Nash equilibrium, and Nash equilibrium is a special case of Bayesian Nash Equilibrium.

3.1.2 Efficiency

A general criterion for evaluating a mechanism is *Pareto efficiency*, meaning that no agent could improve its allocation without making at least one other agent worse off. Another metric of efficiency is *allocative efficiency* which is achieved when the total utility of all the winners is maximized. When allocative efficiency is achieved, the resources or items are allocated to the agents who value them most. These two notions are closely related to each other; in fact, when the utility functions take a special form (such as quasi-linear form (Mas-Collel et al. 1995; Narahari et al. 2009)), Pareto efficiency implies allocative efficiency.

3.1.3 Incentive Compatibility

A mechanism is said to be incentive compatible if it is the best response for all the agents to report their true valuations. There are two kinds of incentive compatibility: dominant strategy incentive compatibility (DSIC) and Bayesian incentive compatibility (BIC). DSIC means that each agent finds it optimal to report its true valuation irrespective of what the other agents report. BIC on the other hand means that each agent finds it optimal to report its true valuation whenever all other agents also report their true valuations. Needless to say, DSIC implies BIC; in fact, BIC is a much weaker notion than DSIC. DSIC is also referred to as strategy-proof property. If a mechanism is strategy proof, each agent's decision depends only on its local information, and there is no need whatsoever for the agent to model or compute the strategies of other agents.

3.1.4 Budget Balance

A mechanism is said to be *weakly* budget balanced if the sum of monetary transfers between the buyer and the sellers is nonnegative, that is, in all feasible outcomes the payments by buyers exceed the receipts of sellers. A mechanism is said to be *strongly* budget balanced if net monetary transfer is zero. In other words, budget balance ensures that the mechanism or the auctioneer does not make losses.

3.1.5 Revenue Maximization or Cost Minimization

In an auction where a seller is auctioning a set of items, the seller would like to maximize total revenue earned. On the other hand, in a procurement auction, the buyer would like to procure at minimum cost. Given the difficulty of finding equilibrium strategies, designing cost-minimizing or revenue-maximizing auctions is not easy. In forward auction, we implicitly assume the cost to the seller, for the goods he is auctioning for, is fixed. In wider settings, this may not be the case and then rather than revenue maximization, the goal of the seller will be profit maximization, where Profit = Revenue − Cost.

3.1.6 Individual Rationality

A mechanism is said to be individually rational (or is said to have voluntary participation property) if its allocations do not make any agent worse off than if the agent had not participated in the mechanism. That is, every agent gains a nonnegative utility by participating in the mechanism.

3.2 *Mechanisms Relevant for Emission Reduction Allocation*

For the problem that we are interested, namely, allocating emission reductions among divisions and partners, the most important properties are incentive compatibility (preferably DSIC), allocative efficiency, minimum budget imbalance, cost minimization, and individual rationality. However, not all of these can be achieved simultaneously (see Mas-Collel et al. 1995; Narahari et al. 2009 for discussion on impossibility results). In this work, our focus is on achieving DSIC, allocative efficiency, and minimizing budget imbalance. DSIC and allocative efficiency are both achieved by the classical Vickrey-Clarke-Groves mechanisms (Vickrey 1961; Clarke 1971; Groves 1973). Among VCG mechanisms, the Groves mechanism (Groves 1973; Mas-Collel et al. 1995; Narahari et al. 2009) is the most general; however, for the current setting, the Clarke mechanism (Clarke 1971; Mas-Collel et al. 1995; Narahari et al. 2009) suffices. We will therefore use the Clarke mechanism as the first approach for solving the emission reduction allocation problem.

Besides DSIC and AE, another property that would be desirable is (strong) budget balance, meaning that the payments are equal to receipts. It is well known that VCG mechanisms are not strongly budget balanced (Mas-Collel et al. 1995; Narahari et al. 2009) and leave a nonzero budget imbalance in the system. In fact, it is impossible to design any mechanism that satisfies strongly budget balance in addition to the other DSIC and AE (Hurwicz 1975; Green and Laffont 1977, 1979; Myerson and Satterthwaite 1983).

In the light of this impossibility result, several authors have obtained budget balance by sacrificing DSIC or AE (Faltings 2005; Parkes et al. 2001; Feigenbaum et al. 2001). Since DSIC and AE are two fundamental properties that we do not want to compromise, the best we can do is to seek mechanisms that satisfy DSIC and AE but minimize the budget imbalance as much as possible. Redistribution mechanisms achieve this by redistributing the VCG payments in a way that DSIC and AE are preserved and budget imbalance is reduced.

To reduce budget imbalance, various rebate functions have been designed by Bailey (1997), Cavallo (2006), Moulin (2009), and Guo and Conitzer (2007). Moulin (2009) and Guo and Conitzer (2007) designed Groves redistribution mechanism for assignment of m homogeneous objects among $n>m$ agents with unit demand. Guo and Conitzer (2007) also considers multiunit auction with nonincreasing marginal values, but the mechanism is applicable only when $m<n$. But in our work, m can be greater than n as each agent has multiple tuples. In another paper by Guo and Conitzer (2008), m need not be less than n but they assumed that a prior distribution over the agents' valuations is available where as in our work the agents valuation can be anything.

A paper by Bhashyam et al. (2011) proposes a worst-case optimal mechanism for allocation of a single divisible item to a number of agents when the agents report only scalar values. It also proposes optimal-in-expectation mechanism where the prior distribution of the agent's types is assumed to be known for the allocation of single divisible item and compares the two mechanisms. The mechanism is applicable to allocation of indivisible goods also, and it simplifies to the mechanism proposed by Guo and Conitzer (2007), where the single good is divided into m equal parts with $m<n$.

In 2006, Cavallo (2006) designed a mechanism that redistributes a large amount of the total VCG payment while maintaining all of the other desirable properties of the VCG mechanism. Cavallo' s mechanism considers how small an agent could make the total VCG payment by changing his/her bid (the resulting minimal total VCG payment is never greater than the actual total VCG payment) and redistributes $1/n$ of that to the agent.

In this work, we extend Cavallo' s mechanism to our allocation setting where there are multiple indistinguishable units of a single good, and each agent's valuation function is concave, that is, agents have nondecreasing marginal values. Also each agent has multiunit demand. For this setting, Cavallo' s mechanism (2006) coincides with a mechanism proposed by Bailey (1997). Cavallo' s mechanism and Bailey's mechanism are in fact the same in any setting, under which VCG mechanisms satisfy revenue monotonicity, for the following reason: Bailey's mechanism redistributes to each agent $1/n$ of the total VCG payment that would result if this agent were removed from the auction. If the total VCG payment is nondecreasing in agents, then, when computing payments under Cavallo's mechanism, the bid that would minimize the total VCG payment is the one that has a valuation of *zero* for everything, which is equivalent to not participating in the auction. Hence, Cavallo's mechanism results in the same redistribution payment as Bailey's. In this work, we refer to this redistribution mechanism as the Cavallo-Bailey redistribution mechanism.

4 A Reverse Auction Protocol for Allocation of Emission Reductions

Consider that there are n players (divisions and partners) and a social planner (company). Let us say that the mandate on the company is to reduce m carbon units. The players submit their carbon reduction cost curves to the company which then allocates reduction units to the divisions. Since the players are strategic, they may not reveal their cost curves truthfully. This necessitates the use of an appropriate mechanism to solve the allocation problem. An elegant solution is to conduct a reverse auction where the social planner tries to procure m units from the n divisions. An immediate way of doing this is by using VCG mechanisms (Vickrey 1961; Clarke 1971; Groves 1973) which satisfy DSIC and AE properties. For this setting, the Clarke mechanism is quite appropriate.

4.1 Clarke Mechanism Applied to the Problem

The Clarke mechanism (Clarke 1971) works by first choosing an optimal outcome based on bidders' reported preferences and then determining the monetary transfers through the Clarke's payment rule. Essentially, to determine the monetary transfer to bidder i, the Clarke payment rule drops player i from the preference aggregation problem and solves a new problem to obtain an optimal outcome without i. The monetary transfer to bidder i is given by the total value of all bidders other than i under an efficient allocation when bidder i is present in the system minus the total value of all bidders other than i under an efficient allocation when bidder i is absent in the system.

4.1.1 An Algorithm for Allocation of Reduction Units

We now present a simple algorithm that is a modified version of the algorithm used in (Parkes et al. 2005) to our setting to obtain an optimal allocation of emission reduction units. The steps in the algorithm are as follows:

- Set initial cost to zero.
- Sort the tuples in an ascending order of their per unit reduction costs. In the case of duplicates, arrange in the ascending order of the size of the tuple $(u_{ij} - u_{i(j-1)})$.

- It can be seen that the problem is similar to a knapsack problem. Pick the tuples in the above order and fill the knapsack. Cost is incremented by the cost of the tuple added to the knapsack.
- If the final tuple cannot completely fit into the knapsack, then consider only the amount that can fit into the knapsack and calculate the cost accordingly.
- Return the total cost.

The final cost returned by the algorithm is the total cost incurred by the company (social planner) in allocating the emission reductions. Cost incurred by each division depends upon the allocation. We provide an example to illustrate the above algorithm.

Example 1

Let a company be interested in procuring 200 emission reduction units from its four divisions. Let the cost curves of the divisions be the following:

Division 1: ((50, 4), (100, 7), (150, 21), (200, 27), (250, 38))
Division 2: ((50, 7), (100, 23), (150, 40), (200, 60), (250, 62))
Division 3: ((50, 16), (100, 32), (150, 59), (200, 77), (250, 104))
Division 4: ((50, 16), (100, 16), (150, 33), (200, 33), (250, 35))

We sort these tuples and apply the given algorithm. We get k = <100, 50, 50, 0>as the allocation vector for the above problem. This means 100 reduction units are allocated to division 1, 50 to division 2, 50 to division 3, and 0 to division 4. The cost incurred by division 1 for the allotment of 100 units is $50*(4+7)$. Similar is the case for divisions 2 and 3. Total cost incurred in performing the reduction is $550+350+800=1{,}700$.

The above allocation turns out to be optimal in this case. In fact, the above algorithm gives a minimum cost solution as proved in [?]. If k is the maximum number of tuples among all the preferences, then the total running time of the above algorithm is $O(kn)$. [AU5]

Example 2

We now illustrate the use of Clarke's mechanism for another illustrative setting. Suppose a company is interested in procuring 120 carbon reduction units from its five divisions. Let the cost curves of the divisions be the following:

Division 1: ((1–10, 4), (11–20, 6), (21–30, 8), (31–40, 10))
Division 2: ((1–10, 3), (11–20, 6), (21–30, 9), (31–40, 12))
Division 3: ((1–10, 6), (11–20, 6), (21–30, 6), (31–40, 6))
Division 4: ((1–10, 8), (11–20, 8), (21–30, 8), (31–40, 8))
Division 5: ((1–10, 6), (11–20, 7), (21–30, 8), (31–40, 9))

An efficient allocation can be achieved by the greedy algorithm. We get k = <30, 20, 40, 10, 20> as the allocation vector for the above problem. This means 30 reduction units are allocated to division 1, 20 to division 2, 40 to division 3, 10 to division 4, and 20 to division 5. By using Clarke's payment rule, the payments made by the company to divisions 1–5, respectively, are <240, 160, 320, 80, 160>. So the total cost to the company is 960.

The Clarke mechanism is allocatively efficient, which minimizes the total cost of achieving the reductions, and it is DSIC. But from the above example, we can see that the company ends up paying a significant amount of money to the divisions. Also, the divisions which are not allocated any reduction units do not make any payments, which results in *free riding*, which is undesirable.

4.2 Cavallo-Bailey Redistribution Mechanism Applied to the Problem

To eliminate the problems in the previous section, we use the Cavallo-Bailey redistribution mechanism. This mechanism results in no deficit to the company. Also, the divisions which are not allocated any reduction units make a nonnegative payment to the company. Using this mechanism, the redistribution payment made by a division to the center is $1/n$ of the total VCG payment that would result if this division were removed from the auction.

Example 3

For the example above (Example 2), by using this redistribution mechanism, the redistribution payments made by the divisions to the center are as follows: <228, 210, 240, 240, 234>. So the net payments made by the company to the divisions are <12, −50, 80, −160, −74>, and the cost to the company is −192. That is, the budget imbalance in the system is 192. We can observe that the cost to the company using this mechanism is very low when compared to that of the Clarke mechanism.

However, using this mechanism, the divisions, even though they do the reductions, might have to pay a certain amount to the company rather than receiving the payment from the company which may not be in the best interest of the divisions unless it is forced to do so. Hence, the mechanism is not individually rational.

5 A Forward Auction Protocol for Allocation of Emission Reductions

In the context of the reverse auction protocol, we have seen that the divisions often have to pay a certain amount to the company rather than receiving the payment from the company. In this section, we propose an innovative forward auction mechanism to circumvent this problem at least under realistic settings. The forward auction is developed through a suitable reinterpretation of the reverse auction problem described above.

In this interpretation, each of the n divisions bid for escape permits to get permits not to reduce. Let us say that each division can perform a maximum of k reductions. Then the maximum number of reductions possible is nk. Let m be the number of reductions required by the company. Then there are a total of $nk-m$ escape permits for sale. This now becomes a forward auction problem. Using this reinterpretation, we can simply run a (forward) VCG auction for the $nk-m$ permits. The VCG payments made by the divisions depend on the number of permits they bought to avoid reductions. We can call this VCG payment as green tax. The higher the number of escape permits they buy, the higher is the tax they pay. Then this VCG payment collected from the divisions can be redistributed to all the divisions using the Cavallo-Bailey redistribution mechanism. The algorithm to do this is as follows:

- Sort the tuples in nonincreasing order of their per unit reduction costs.
- If x is the maximum number of reductions possible by all the divisions and m is the number of reductions required by the company, then there are $x-m$ escape permits that can be given to the divisions. Allocate these permits to the divisions in decreasing order of their per unit reduction costs using VCG mechanism.
- The resulting budget imbalance is redistributed to the divisions using Cavallo-Bailey redistribution mechanism.

Example 4

In the example above (Example 2), the number of reduction units required by the company is $m=120$. In this example, the total number of reductions possible is $x=200$. Hence, there are 80 escape permits for sale. Allocate these 80 permits to the divisions using the Clarke mechanism. Then the allocation vector is <10, 20, 0, 30, 20>. That is, 10 permits to division 1, 20 permits to division 2, 0 permits to division 3, 30 permits to division 4, and 20 permits to division 5. The VCG payments made by the divisions to the center for buying the permits are <80, 160, 0, 210, 160>. Now, applying Cavallo-Bailey mechanism, these payments can be redistributed to the divisions. The redistribution payments made by the center to the divisions are <100, 100, 122, 96, 96>. The budget imbalance (payments minus the receipts) is 96 which is very low compared to the budget imbalance of 192 in the reverse auction problem setting.

As we can see in the above example, division 3 does not buy any escape permits; hence, the payment (tax) made by division 3 is 0. This will apply to any division not buying permits, and the tax paid by such divisions is 0. Also, they get a nonnegative redistribution amount. So, unlike the reverse auction problem, here, only the divisions buying the escape permits to avoid reductions pay the tax (VCG payment). This ensures that no divisions would free ride the reduction emission process. The total amount collected is redistributed to all the divisions.

6 Comparison of Reverse and Forward Auction Protocols: A Case Study

In this section, we describe a stylized case study involving a global company consisting of five divisions which contribute to carbon emissions by the company. We experiment with three representative cases of cost curves for the divisions. In the first case, the cost curves are similar and have minor variations across the divisions. In the second case, the cost curves exhibit major variations across the divisions.

Table 1 Solution 1: Reverse auction protocol

Division	Number of reductions allocated	Payment made by center to division	Redistribution payment by division to center	Net payment by division to center
1	30	240	228	−12
2	20	160	210	50
3	40	320	240	−80
4	10	80	240	160
5	20	160	234	74

The third case examines a situation where the cost curves exhibit some extreme characteristics. It turns out that all the three cases are realistic in their own way since they represent different types of global company organizations. The purpose of the experimentation is to examine how the two protocols based on reverse auction and forward auction handle the allocations and payments. In particular, we are also interested in the budget imbalance exhibited by the two protocols.

6.1 *Case 1: Cost Curves with Minor Variations*

Here, we consider the case of divisions which have comparable costs for reductions. The cost curves are provided below. Assume that the number of reduction units required by the company (center) is 120.

Division 1: ((1–10, 4), (11–20, 6), (21–30, 8), (31–40, 10))
Division 2: ((1–10, 3), (11–20, 6), (21–30, 9), (31–40, 12))
Division 3: ((1–10, 6), (11–20, 6), (21–30, 6), (31–40, 6))
Division 4: ((1–10, 8), (11–20, 8), (21–30, 8), (31–40, 8))
Division 5: ((1–10, 6), (11–20, 7), (21–30, 8), (31–40, 9))

Solution 1: Reverse Auction Setting
Table 1 shows the results for this setting. The table lists, for each of the divisions, the number of reductions allocated, VCG payment by center to division, redistribution payment by division to center, and net payment made by the division to the center.

- Using the VCG mechanism, the allocation vector is $k = \langle 30, 20, 40, 10, 20 \rangle$. This means 30 reduction units are allocated to division 1, 20 to division 2, 40 to division 3, 10 to division 4, and 20 to division 5.
- The VCG payments made by the company to divisions 1–5, respectively, are $\langle 240, 160, 320, 80, 160 \rangle$.
- The redistribution payments made by the divisions to the center are as follows: $\langle 228, 210, 240, 240, 234 \rangle$.
- The budget imbalance in the system is 192. The divisions are required to pay an amount of 192 monetary units to the center. Note that division 1 and 3 are receiving appropriate amounts from the center since they are performing substantial

Table 2 Solution 2: Forward auction protocol

Divisions	Number of escape permits	Number of reductions done	Tax levied on divisions	Redistribution payment by center to division	Net payment by division to center
1	10	30	80	100	−20
2	20	20	160	100	60
3	0	40	0	122	−122
4	30	10	210	96	114
5	20	20	160	96	64

carbon reductions. The other divisions are paying appropriate amounts to the center due to relatively lesser number of reductions they are allocated.

Solution 2: Forward Auction Setting
In the current problem, the total number of reductions that are possible by all the divisions is 200. As the number of reduction units required by the company is 120, there are 80 escape permits that can be given to the divisions. Table 2 shows the results for this setting. The table lists, for each of the divisions, the number of escape permits allocated, number of reductions done, VCG payment by division to center (which we call tax levied), redistribution payment by center to division, and net payment made by the division to the center.

- Using the VCG mechanism, the allocation vector of escape permits is k=<10, 20, 0, 30, 20>. This means 10 permits are given to division 1, 20 to division 2, 0 to division 3, 30 to division 4, and 20 to division 5.
- The VCG payments (or green tax paid) by the divisions 1–5 to the center are <80, 160, 0, 210, 160>.
- The redistribution payments made by the center to the divisions are <100, 100, 122, 96, 96>.
- The budget imbalance in the system is 96. Note that the budget imbalance is much less compared to the amount of 192 in the reverse auction setting. Now divisions are required to pay an amount of 96 monetary units to the center. Note that division 1 and division 3 are receiving appropriate amounts from the center since they are performing substantial carbon reductions (the amounts received are higher than those in the case of reverse auction setting). The other divisions are paying appropriate amounts to the center as they buy more number of escape permits and perform less number of reductions.

6.2 Case 2: Cost Curves with Wide Variations

Here, we consider a more realistic scenario where the cost curves are not as similar as in case 1. Division 1 incurs different per unit cost in the four intervals (1–10), (11–20), (21–30), and (31–40). Division 2 incurs the same per unit cost in the entire interval (1–40). Division 3 cannot reduce more than 30 units and division 4 cannot

Table 3 Solution 1: Reverse auction protocol

Division	Number of reductions allocated	Payment made by center to division	Redistribution payment by division to center	Net payment by division to center
1	30	240	184	−56
2	0	0	204	204
3	20	160	162	2
4	20	160	162	2
5	20	160	168	8

reduce more than 20 units. Finally, division 5 has a per unit cost of 5 in the interval (1–20) and a per unit cost of 11 in the interval (21–40). Assume that the number of reduction units required by the company is 90.

Division 1: ((1–10, 4), (11–20, 6), (21–30, 8), (31–40, 12))
Division 2: ((1–40, 8))
Division 3: ((1–20, 5), (21–30, 12), (31–40, ∞))
Division 4: ((1–20, 3), (21–40, ∞))
Division 5: ((1–20, 5), (21–40, 11))

Solution 1: Reverse Auction Setting
Table 3 shows the results for this setting. The table lists, for each of the divisions, the number of reductions allocated, VCG payment by center to division, redistribution payment by division to center, and net payment made by the division to the center.

- Using the VCG mechanism, the allocation vector is k=<30, 0, 20, 20, 20>. This means 30 reduction units are allocated to division 1, 0 to division 2, 20 to division 3, 20 to division 4, and 20 to division 5.
- The VCG payments made by the company to divisions 1–5, respectively, are <240, 0, 160, 160, 160>.
- The redistribution payments made by the divisions to the center are as follows: <184, 204, 162, 162, 168>.
- The budget imbalance in the system is 160. Note that division 1's net payment is −56 which means it is receiving a net payment of 56 monetary units from the center. This is because of the large number of reductions allocated to this division.

Solution 2: Forward Auction Setting
Here, the cost curves are such that the total number of reductions that are possible by all the divisions is 170. As the number of reduction units required by the company is 90, there are 80 escape permits that can be assigned to the divisions. Table 4 shows the results for this setting. The table lists, for each of the divisions, the number of escape permits allocated, number of reductions done, VCG payment by division to center (which we call tax levied), redistribution payment by center to division, and net payment made by the division to the center.

- Using the VCG mechanism, the allocation vector of escape permits is k=<10, 40, 10, 0, 20>. This means 10 permits are given to division 1, 40 to division 2, 10 to division 3, 0 to division 4, and 20 to division 5.

Table 4 Solution 2: Forward auction protocol

Divisions	Number of escape permits	Number of reductions done	Tax levied on divisions	Redistribution payment by center to division	Net payment by division to center
1	10	30	50	72	−22
2	40	0	240	68	172
3	10	20	80	80	0
4	0	20	0	102	−102
5	20	20	140	68	72

- The VCG payments (or green tax) made by divisions 1–5 to the center are <50, 240, 80, 0, 140>.
- The redistribution payments made by the center to the divisions are as follows: <72, 68, 80, 102, 68>.
- The budget imbalance in the system is 120, which is less than 160 incurred in the reverse auction setting. Now divisions are required to pay an amount of 120 monetary units to the center. Note that division 1 and division 4 are receiving appropriate amounts from the center since they are performing substantial carbon reductions. Divisions 2 and 5 are paying appropriate amounts to the center as they buy more number of escape permits and perform less number of reductions. It is interesting to note that division 3 is not paying (receiving) any amount to (from) the center.

6.3 Case 3: Cost Curves with Extreme Variations

Now we consider cost curves which have wide variations. Such cost curves may not be unrealistic. Let the number of reduction units required by the company be 90. The cost curves are as follows.

Division 1: ((1–40, 50))
Division 2: ((1–20, 4), (21–40, 60))
Division 3: ((1–20, 5), (21–30, 8), (31–40, ∞))
Division 4: ((1–20, 3), (21–40, ∞))
Division 5: ((1–20, 5), (21–40, 10))

Solution 1: Reverse Auction Setting
Table 5 shows the results for this setting. The table lists, for each of the divisions, the number of reductions allocated, VCG payment by center to division, redistribution payment by division to center, and net payment made by the division to the center.

- Using the VCG mechanism, the allocation vector is k=<0, 20, 30, 20, 20>. This means 0 reduction units are allocated to division 1, 20 to division 2, 30 to division 3, 20 to division 4, and 20 to division 5.
- The VCG payments made by the company to the divisions 1–5, respectively, are <0, 200, 700, 200, 1,000>.
- The redistribution payments made by the divisions to the center are as follows: <480, 900, 940, 900, 960>.

Table 5 Solution 1: Reverse auction protocol

Division	Number of reductions allocated	Payment made by center to division	Redistribution payment by division to center	Net payment by division to center
1	0	0	480	480
2	20	200	900	700
3	30	700	940	240
4	20	200	900	700
5	20	1,000	960	–40

Table 6 Solution 2: Forward auction protocol

Divisions	Number of escape permits	Number of reductions done	Tax levied on divisions	Redistribution payment by center to division	Net payment by division to center
1	40	0	230	64	166
2	20	20	130	72	58
3	0	30	0	72	–72
4	0	20	0	98	–98
5	20	20	130	64	66

- The budget imbalance in the system is 2080. Note that only division 5 is receiving a net payment from the center while all other divisions are paying up heavily to the center.

Solution 2: Forward Auction Setting

Note that the total number of reductions that are possible by all the divisions is 170. As the number of reduction units required by the company is 90, there are 80 escape permits that can be given to the divisions. Table 6 shows the results for this setting. The table lists, for each of the divisions, the number of escape permits allocated, number of reductions done, VCG payment by division to center (which we call tax levied), redistribution payment by center to division, and net payment made by the division to the center.

- Using the VCG mechanism, the allocation vector of the permits is $k = \langle 40, 20, 0, 0, 20 \rangle$. This means 40 permits are given to division 1, 20 to division 2, 0 to division 3, 0 to division 4, and 20 to division 5.
- The VCG payments (green tax) made by the divisions 1–5, respectively, are $\langle 230, 130, 0, 0, 130 \rangle$.
- The redistribution payments made by the center back to the divisions are as follows: $\langle 64, 72, 72, 98, 64 \rangle$.
- The budget imbalance in the system is 120 which is far less compared to the 2080 obtained in the case of the reverse auction protocol. This clearly shows that the forward auction is able to handle extreme cases such as these very well. Another desirable feature here is the fact that divisions 3 and 4 are now receiving a net payment from the center in recognition of the substantial reductions they are able to carry out.

6.4 Summary of Experiments

We summarize the results of our experiments below.

- From the above representative examples, we can see that the forward auction protocol reduces the budget imbalance compared to the reverse auction protocol under the settings considered. However, this does not prove that the forward auction will always lead to less budget imbalance compared to the reverse auction protocol. This needs a more detailed study.
- In the forward auction protocol, a penalty (green tax) is paid by only those divisions who buy escape permits not to carry out emission reduction. The divisions that do not buy any escape permits do not pay any tax since they are allocated zero escape permits, and hence the VCG payment they incur is zero. The higher the number of escape permits they buy, the higher would be the tax they will have to pay. The tax thus collected by the center is redistributed by the center to the divisions that perform emission reductions. Thus, our goal of rewarding divisions that reduce emissions and levying a penalty on those who do not participate in emission reductions is achieved.
- In all the cases, there is a nonzero overall net payment from the divisions to the center. In the forward auction setting, this has a natural interpretation as these payments are made by the divisions that buy escape permits in order not to participate in carbon emission reductions.
- Results shown in Table 1 bring out a drawback of the reverse auction protocol: we see that even though divisions 3 and 4 carry out maximum number of reductions possible (30 and 20 units, respectively), they end up paying significant amounts of money to the center. In the same breath, results shown in Table 2 bring out a virtue of the forward auction protocol: we see that divisions 3 and 4, instead of paying to the center, actually receive incentive payments from the center.
- Another specific conclusion that can be drawn from case 3 and solution 2 (where the cost curves of the divisions are highly asymmetric) is that budget imbalance is reduced by the use of the forward auction protocol. However, we wish to add immediately that there could be certain scenarios where the reverse auction protocol may perform better.

We emphasize again that both the protocols above satisfy two extremely desirable properties, namely, AE and DSIC.

7 Conclusion

In this work, we addressed the specific problem faced by a global industry or global company in allocating emission reductions to its different divisions and supply chain partners towards achieving a required target in its carbon reduction program. Since the divisions and supply chain partners are autonomous and could exhibit strategic behavior, the problem was modeled as a mechanism design problem.

We first proposed the use of a reverse auction protocol where the company procures reduction units from the divisions and partners based on cost curves reported by them. The use of a straightforward Vickrey-Clarke-Groves (VCG) mechanism for this reverse auction leads to an allocatively efficient and truthful reverse auction protocol for allocating carbon reductions among emitting agents. However, the resulting budget imbalance was found to be high. To reduce budget imbalance, we proposed the use of the Cavallo-Bailey redistribution mechanism. We also proposed an innovative forward auction protocol which seems to yield fewer imbalances when combined with the Cavallo-Bailey redistribution mechanism.

The experimentation in this work is limited to a stylized case study with three representative scenarios. The numerical results show that the forward auction protocol performs better in reducing budget balance. However, this observation is at best empirical. We propose to carry out a detailed simulation study to investigate the relative performance of the two protocols. In fact, it would be of great interest to compare these two protocols in the context of a real-world case study; however, obtaining data (cost curves for emission reductions) for real-world scenario is extremely difficult.

The mechanisms proposed in the work have focused on three properties, namely, DSIC, AE, and reduced budget imbalance. There is abundant scope for investigating other properties such as individual rationality and cost minimization. Another direction for future work would be to come up with a mechanism that is DSIC and strictly budget balanced. Such a mechanism will invariably not satisfy allocative efficiency, so one can try to minimize the loss of efficiency.

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AU2	Please confirm equation in sentence "To obtain *n*, we …" is appropriate.	
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AU5	Please check the occurrence [?].	
AU6	Please provide publisher and location details for reference "Ellerman and Joskow (2008)".	
AU7	Please provide location details for Guo and Conitzer (2007, 2008).	
AU8	Please provide year of publication for reference "Kyoto protocol".	
AU9	Please provide complete details for the reference "Arava et al. (2010b)" and "United Nations Industrial Development Organization Report (2007)".	