Mechanism design problems in carbon economics

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Abstract | Reduction of carbon emissions is of paramount importance in the context of global warming and climate change. Countries and global companies are now engaged in understanding systematic ways of solving carbon economics problems, aimed ultimately at achieving well defined emission targets. This paper proposes mechanism design as an approach to solving carbon economics problems. The paper first introduces carbon economics issues in the world today and next focuses on carbon economics 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). It is argued that these problems are best addressed as mechanism design problems. The discipline of mechanism design is founded on game theory and is concerned with settings where a social planner faces the problem of aggregating the announced preferences of multiple agents into a collective decision, when the actual preferences are not known publicly. The paper provides an overview of mechanism design and presents the challenges involved in designing mechanisms with desirable properties. To illustrate the application of mechanism design in carbon economics, the paper describes in detail one specific problem, the carbon credit allocation problem.

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1. Introduction

The earth now has a variety of environmental problems which affect the whole world. As development continues across the globe, the earth's natural processes transform local problems into international issues. Acid rain, air pollution, global warming, hazardous waste, Ozone depletion, smog, water pollution, overpopulation and rain forest destruction are some of the major environmental problems that we face today. Climate change and associated phenomena of global warming have emerged as a challenge to sustainable development. A report by the intergovernmental panel of climate change finds that the global surface temperature increased by 0.74±0.18 degree Celsius between the start and the end of the 20th century. It concludes saying that this is a direct consequence of excessive human activities such as fossil fuel burning, deforestation and certain types of farming methods, which has increased the concentration of green house gases (water vapor, carbon dioxide, methane, nitrous oxide, ozone and chlorofluorocarbons). They absorb and emit radiation within thermal infrared range. Increase in global temperature will result in sea level to rise and will change pattern and amount of precipitation, including the expansion of subtropical deserts. Warming is expected to be stronger in north pole and may result in continuing retreat of glaciers, permafrost and sea ice. Further, they affect changes in the frequency and intensity

Table 1: Acronyms used in the paper.

AAU	Assigned Amount Units
AE	Allocatively Efficient
BIC	Bayesian Incentive Compatible
CCA	Carbon Credit Allocation
CCB	Carbon Credit Buying
CCS	Carbon Credit Selling
CCE	Carbon Credit Exchange
CCFE	Chicago Climate Futures Exchange
CCX	Chicago Climate Exchange
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CFI	Carbon Financial Instrument
DSIC	Dominant Strategy Incentive Compatible
ECX	European Climate Exchange
EEX	European Energy Exchange
EPE	Ex-post Efficient
ETS	Emission Trading System
EU	European Union
EUA	European Union Allowances
GHG	Green House Gas
ICCAF	Internal Carbon Credit Allocation Framework
ICMG	Internal Carbon Management Group
IEA	International Environment Agreement
IPCC	Intergovernmental Panel on Climate Change
ICX	India Climate Exchange
IR	Individually Rational
JI	Joint Implementation
MAC	Marginal Abatement Cost
NAP	National Allocation Plan
RMU	Removal Unit
UNFCCC	United Nations Framework Convention on Climate Change
VCG	Vickrey–Clarkes–Groves Mechanism
VER	Voluntary Emission Reduction

of extreme weather events, extinction of species, changes in agricultural yields. These changes are likely to vary across different regions of the globe, although the nature of variations are uncertain. Scientific, political and public debate on global warming continues to find what actions to take in response. Some practical options are reduction in emissions, mitigate the damage caused by warming. Radical options using geo engineering to reverse global warming, etc. are also debated.

World-wide, there has been a quite intense activity by all countries and global organizations to address the issues raised by climate change and global warming. This paper is concerned with an important current problem facing most global industries in the world, namely, to find optimal strategies for carbon economics problems. The paper first introduces carbon economics issues in the world today and next focuses on carbon economics problems facing global industries. The paper identifies several decision making problems faced by global industries in the context of carbon economics. The paper shows that these problems can be addressed in a natural way as mechanism design problems. The discipline of mechanism design [1] is founded on game theory and is concerned with settings where a social planner faces the problem of aggregating the announced preferences of multiple agents into a collective decision, when the actual preferences are not known publicly. The paper provides an overview of mechanism design and presents the challenges involved in designing mechanisms with desirable properties. The paper then describes in detail one specific problem, the carbon credit allocation problem.

1.1. *Outline of the paper*

The rest of the paper is organized as follows.

- **Section 2: Issues in carbon economics**: This section covers important relevant issues in carbon economics arising out of the current ongoing efforts to combat the detrimental effects of climate change and global warming. The section starts with an overview of global efforts to address climate change followed by a description of three important instruments for reduction of emissions, namely *Joint Implementation*, *Clean Development Mechanism*, and *Emissions Trading*. This is followed by an introduction to some issues in carbon trading and a description of climate exchanges. Finally, this section describes different forms of carbon trading including the extensively used *cap and trade* mechanisms.
- **Section 3: Carbon economics in global industries**: This section focuses on carbon economics issues faced by global industries. The section starts by introducing a carbon planning framework that would be required by any global industry that aspires to accomplish carbon reduction in a systematic way. This is followed by a description of four representative carbon economic problems underlying the carbon planning framework: *carbon credit allocation (CCA) problem*, *carbon credit buying (CCB) problem*, *carbon credit selling (CCS) problem*, and *carbon credit exchange (CCE) problem*.
- **Section 4: Mechanism design**: This section provides an overview of mechanism design. The section starts by listing the characteristics of the CCA, CCB, CCS, and CCE problems

and motivates the use of mechanism design to solve the problems. The rest of this section presents an overview of mechanism design covering the history, game theoretic foundations, properties, and important results of mechanism design.

- **Section 5: Carbon allocation mechanism**: This section studies one particular problem, the carbon credit allocation problem, in some detail. Different possible mechanisms, satisfying different subsets of desirable properties, are presented for this problem.
- **Section 6: Conclusions and future work**: After providing a summary of the paper, this section provides several directions for future work.
- **Section 7: Glossary**: This section includes a glossary with a crisp description of many important concepts and notions that are relevant to the current paper.

Finally a representative list of references is provided.

2. Carbon economics: some issues

In this section, we present some important relevant issues in carbon economics arising out of the current ongoing world-wide efforts in the context of climate change and global warming. We first provide an overview of global efforts to address climate change followed by a description of three important instruments for reduction of emissions, namely Joint Implementation, Clean Development Mechanism, and Emissions Trading. Next we introduce some issues in carbon trading and describe climate exchanges. Finally, we describe different forms of carbon trading including the extensively used cap and trade mechanisms.

2.1. *Global efforts towards climate change*

The need to address environmental problems of international dimension through coordinated action was clearly recognized as early in 1971, in the first report to the Club of Rome. It was further elaborated at the conference on Environment and Development in Stockholm in 1972 and in the First environmental action programme of the European community in 1973. In order to evaluate the effectiveness of the existing international environmental agreements, it is necessary to know how negotiations on certain issues evolved, on what exactly the cooperating parties agreed and how successfully these agreements have been implemented so far. In June 1992, with the aim of achieving significant reductions in GHG emissions, more than 170 nations signed the United Nations Framework Convention on Climate Change (UNFCCC) at the Earth Summit, held in Rio de Janeiro in June 1992. It sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change. It recognizes that the climate is a shared resource whose stability can be affected by industrial and other emissions of carbon dioxide and other greenhouse gases. The ultimate objective of the convention is a stabilization of green house gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. This goal is to be achieved in two steps: first by reducing present global GHG emissions to appropriate levels, and second by stabilizing the atmospheric GHG concentrations in the long run. The first conference of the parties (COP-I) in 1995 neither agreed on explicit reduction targets nor discussed the financial aspects of international climate policy, but it's important outcome is "Berlin Mandate" an agenda to continue negotiating on binding commitments of industrialized countries after the year 2000. The second conference of the parties (COP-II) took place in 1996, in Geneva, to give a fresh impetus to the negotiations on a binding protocol. It produced Geneva Ministerial Declaration that emphasized the need to accelerate the Berlin Mandate talks on strengthening the convention, in particular by making the commitments in the post-2000 period legally binding. In 1997, the negotiations following the Rio Convention finally resulted in a binding protocol which specifies explicit reduction targets for the most important GHG-emitting countries.

2.1.1. *Kyoto Protocol*

The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005 and hence called as "Kyoto Protocol". The detailed rules for the implementation of the Protocol were adopted at COP 7 in Marrakesh in 2001, and are called the "Marrakesh Accords" [2]. The Kyoto Protocol agreed on enlarging the basket of greenhouse gases from three to six gases and added new sinks for GHG like tropical rain forests etc.

Kyoto Protocol [2] separates the parties ratifying the protocol into Annex I, Annex II and developing countries. Under the UNFCCC framework the industrialised countries and economies in transition are listed as Annex I. These countries have an obligation to help developing countries to mitigate climate change. Annex II countries are the subset of Annex I countries that have an obligation to provide additional technology and financial assistance to help developing countries reduce emissions. Kyoto Protocol stipulates a reduction and limitation of GHG emissions by Annex I countries which ensures a collective decrease in GHG emissions by at least 5 percent below 1990 levels within the first period of commitment from 2008 to 2012. To fulfill the overall emission reduction target, the member states of the European Union (EU) as a group committed themselves to a reduction in their GHG emissions of 8 percent with respect to 1990 levels, the USA 7 percent, and Japan 6 percent. Other important GHG emitting countries such as China and India however are not subject to any abatement obligations at all. Although this goal is compatible with further increasing global CO_2 emissions during the next few decades, emissions will then have to decline drastically and must converge in the long run to approximately half of current annual emission quantities. However, long term stabilization of emissions will be a difficult task considering increases in annual energy consumption in conjunction with a growing population. Kyoto Protocol provides for several flexible instruments whose purpose is to increase the international cost-effectiveness of emission reductions.

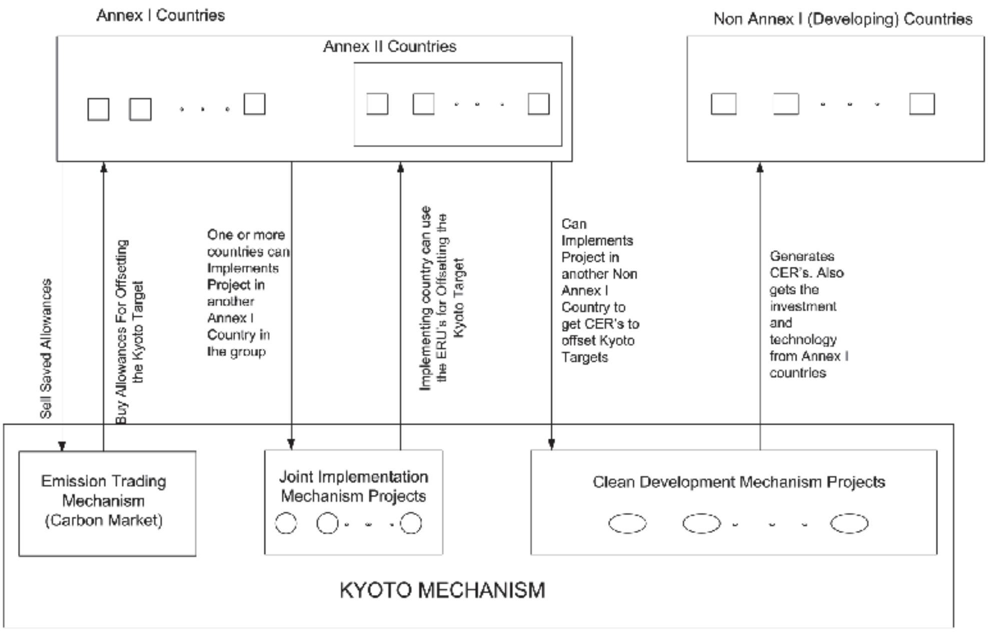
The Kyoto Protocol[2] defines three innovative “flexible mechanisms” to lower the overall costs of achieving its emissions targets. These mechanisms enable countries that have obligations to reduce greenhouse gas emissions under the Kyoto Protocol, to access cost-effective opportunities to reduce greenhouse gas emissions. These mechanisms believe that the cost of limiting emissions varies considerably across regions and sectors, the benefit for the atmosphere is the same, wherever the action is taken.The Kyoto Protocol allows for developed countries to reduce their emissions using certain mechanisms (1) Joint Implementation (2) Clean development Mechanism and (3) Emission Trading.

Joint Implementation (JI)

Under Joint Implementation Mechanism[2] emission reduction projects can be implemented jointly by two (or more) Annex I countries in another Annex I country (Figure 1), and count the resulting emission reduction units (ERU’s) towards meeting the Kyoto target of the other involved Annex I countries. In other words, JI allows a developed country with an emission reduction or limitation commitment under the Kyoto Protocol to earn cost efficient ERU’s from an emission-reduction or emission removal project in another developed country, each equivalent to one tonne of CO_2, which can be counted towards meeting its Kyoto target.

Under Kyoto protocol, emissions are limited or capped and called as Allowed emissions. The JI projects reduce emissions in the host country (where the project has been implemented) and free up part of their total amount which can then be transferred to the investor country in the form of ERUs (Figure 1). These are then subtracted from the host country’s allowed emissions, and added to the total allowable emissions of the investor country. JI also enables the transfer of efficient technologies and

Figure 1: Kyoto Framework.



best available practices to the host countries. For investing countries, JI helps to meet their emission targets under the Kyoto Protocol in a cost effective way.

To participate in Joint Implementation as a host or investor, parties must originate from an Annex I country with emissions caps as listed in Annex B to the Kyoto Protocol. The countries also need to meet a set of six eligibility requirements to be allowed to engage in transference and acquisition of ERUs generated in JI projects[2].The six eligibility requirements outlined in relevant guidelines of the Kyoto Protocol. As the host country also has a target under the Kyoto Protocol, a JI project must reduce emissions against a 'business as usual' baselines, in order to free up Emission Reduction Units (ERUs) to sell.

As a buyer in JI projects the countries like Netherlands, Denmark and Austria are currently the most active buyers where as countries like Russia, Ukraine, Bulgaria, Romania and Poland are big sellers in the JI projects.

Clean Development Mechanism (CDM)

Clean Development Mechanism[2] allows a developed country with an emission reduction or emission limitation commitment under the Kyoto Protocol (Annex I countries) to implement an emission reduction project in developing countries (Figure 1) (non-Annex I countries).

It enables industrialized countries with emissions reductions commitments to meet their targets, in a cost efficient way. The incentive to invest in projects is created by the different costs of carbon abatement an industrialized country seeking to reduce emissions domestically is likely to face substantially higher costs, compared to implementing emission reduction project in developing countries.

It is the first global, environmental investment and credit scheme of its kind, providing a standardized emissions offset instrument, CERs. Projects hosted in non-Annex I countries, such as Asia, South Africa and South America, may be developed unilaterally, or bilaterally with investment or support from companies and Governments in Annex I countries. Such projects can earn tradable certified emission reduction (CER) credits, each equivalent to one tonne of CO_2. Also the projects must qualify through a rigorous and public registration and issuance process designed to ensure real, measurable and verifiable emission reductions that are additional to what would have occurred without the project. The mechanism is overseen by the CDM Executive Board, answerable ultimately to the countries that have ratified the Kyoto Protocol.

A CDM project activity might involve, for example, a rural electrification project using solar panels or the installation of more energy-efficient boilers. The mechanism stimulates sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission reduction or limitation targets. CDM is currently the most commonly used mechanism for the developing countries like India and China. Currently a total of 2229 CDM projects have been registered that can generate 360 million CER's annually. Among these a total of 509 projects have been registered by India, China been at the top with 862 projects.

Emission Trading (ET)

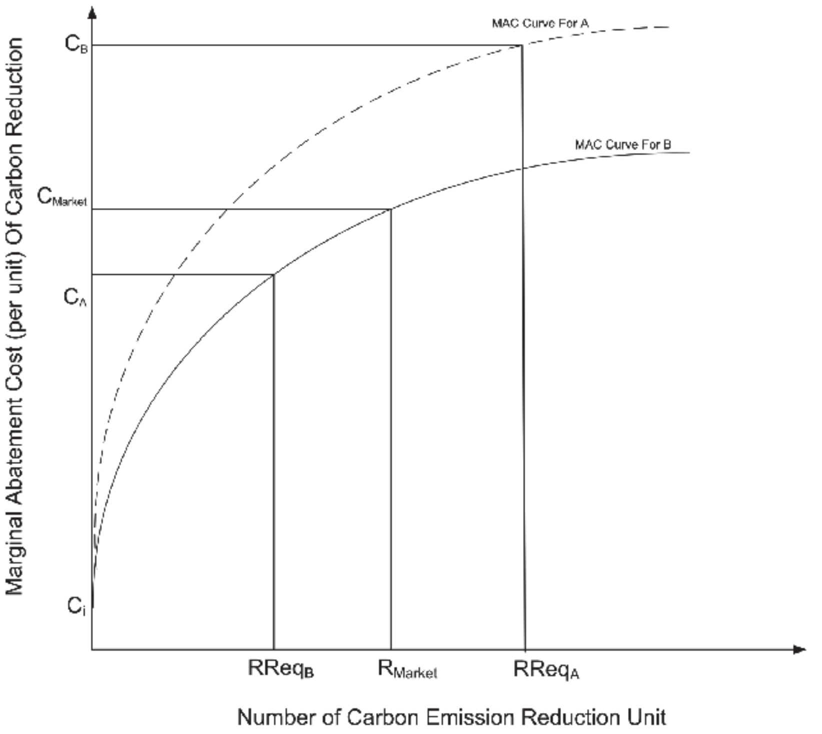
This is an incentive mechanism for the parties committed to the Kyoto Protocol. Under this mechanism developed countries mutually trade emissions allocation. It implies that each party has accepted allowed emission targets over the 2008–2012 decided with respect to their 1990 emission levels. Allowed Emissions are divided into Assigned Amount Units (AAUs) and this puts a cap on number of units of allowed emission by these parties. Each AAU gives the holder the right to emit one tonne of CO_2. The parties that have their emission levels less than the allowed emission, can trade this excess emission to the parties that are over their allowances through different exchanges. Thus a new commodity is formed in the form of emission reductions or removals. GHG emissions are tracked and traded like any other commodity. Since carbon dioxide is the principal GHG hence the phrase carbon trading refers to all GHG trading.

The motivating factor for emission trading is the difference of the cost of reducing the emission at two different emission sources. The cost for eliminating one tonne of CO_2 is called the Marginal Abatement Cost (MAC). The countries or industries has more abatement cost can buy emission allow from those who pollute less. It is this flexibility in the system which makes emissions trading the most cost-effective way of achieving a given environmental target.

An example:

As an example, let us consider two emission sources say A and B with the MAC of A is higher than that of B. The cost curves of A and B are shown in Figure 2. The costs are most appropriately modeled as no-decreasing curves. The cost C_i is the initial cost for both A and B, before any emission reduction can be obtained. Let the allowance or AAU be the same for A and B and be given by R^*. Now A and B have to reduce their emission to the

Figure 2: Unit cost of reduction as a function of emission reduction unit.



level less than or equals to R^*. Let the emission reduction requirement for A and B be $RReq_A$ and $RReq_B$ to meet the cap R^*. Let C_{Market} be the cost of carbon reduction if purchased from the carbon market and R_{Market} be the equivalent reductions that can be purchased. The cost C_A and C_B be the cost incurred for achieving $RReq_A$ and $RReq_B$ units of the emission reductions by A and B respectively.

As we can see from Figure 2, B can reduce more carbon units than required at lesser cost than the market price. But for A to reach the required reduction it has to spend more than market price if A does the reduction at its own end.

Hence B can reduce emission units $\leq R_{Market} - RReq_B$ and can sell these units to A at an appropriate cost. Thus the difference in the marginal abatement cost of A and B motivates the trading between A and B.

For each trading period under the scheme, parties under Kyoto Protocol draw up national allocation plans (NAP) which determine how many emission allowances each installation receives. The Emission trading directive decides the criteria which the countries have to respect while issuing the allowances, in order to participate in the Emission Trading System (ETS). A country or party cannot be overgenerous in issuing allowances and have to comply with some of the allocation criteria. Scarcity of allowances is required to develop the carbon market. The parties committed to Kyoto Protocol can invest in Joint Implementation and Clean Development Mechanism to gain credits and use them to count the achieved reductions against their Kyoto Targets. The companies that keep their emissions below the level of their allowed allowances can sell their excess allowances. Those facing difficulty in keeping their emissions in line with their allowances have a choice between taking measures to reduce their own emissions, such as investing in more efficient technology or using less carbon-intensive energy sources, or buying the extra allowances they need on the market, or a combination of the two. Such choices are likely to be determined by relative costs. In this way, emissions are reduced wherever it is most cost effective to do so.

Reduction of emissions would require cooperation from various sectors of economy, thus the best approach is to adopt a diversified portfolio of policies that addresses all major sectors. For these policies to be effective, special attention has to be paid for identifying and removing barriers of innovation, addressing factors like that do not incorporate externalities such as pollution, misplaced incentives, vested interests, lack of effective regulatory agencies and imperfect information.

2.2. *Regional responses to climate change*

Europe and European Union

All European Union (EU) states have ratified the Kyoto Protocol. In January 2005 the EU introduced its European Union Emission Trading Scheme (EU ETS), through which companies in conjunction with government agree to cap their emissions or to purchase credits from those below their allowances. Any organization trading through the ETS should also meet the international trading obligations under Kyoto. EU ETS is the cornerstone of the EU's strategy for fighting climate change. It is the world's first and largest international trading system for CO_2 emissions and has resulted in rapid expansion of carbon trading around the world. It covers over 10,000 installations in the energy and industrial sectors which are collectively responsible for close to half of Europe's emissions of CO_2. The aim of the EU ETS is to help EU Member States achieve compliance with their commitments under the Kyoto Protocol in a cost-effective way. Letting participating companies buy or sell emission allowances means that emissions cuts can be achieved at least cost. If the Emissions Trading Scheme had not been adopted, other more costly measures would have had to be implemented.

United States of America

In 1998, Vice President of United States, Al Gore signed the Kyoto Protocol. However, it was indicated that participation by the developing nations was necessary prior to being submitted for ratification by the United States Senate. Under the principle of common but-differentiated responsibilities, the developing nations refused to commit to reduce emissions. As of June 2009, the US has refused to ratify the treaty even though it is historically the world's largest emitter of greenhouse gases. However, the interest of US in cutting down emissions is visible as President Barack Obama has announced plans to introduce an economy-wide cap and trade scheme. Moreover, the trade volumes in CCX also indicate the same.

India

Developed Countries are responsible for the largest share of historical and current global GHG emissions while the per capita emissions in developing countries are relatively low. Moreover, for the developing countries to progress, their share of global emissions would have to increase to meet the growing social and development needs. Thus the UNFCCC agreed to a set of a "common but differentiated responsibilities" wherein any of the developing countries including India were not included in any numerical limitation of the Kyoto Protocol, but they were to share the common responsibility of all countries to reduce emissions. This means that while the industrialized countries have to cut down emissions as a part of commitment, India also needs to do its part. The mitigation in India is mainly via CDM projects registered with the UNFCCC. These emissions reductions generate CERs. Moreover, Voluntary Emission Reductions (VERs) are the emission reductions which could not be a part of CDM project activities due to technical or some other reasons. Moreover, the establishment of India Climate Exchange (ICX) is underway and is being controlled by the CCX.

2.3. *Carbon trading*

Carbon trading is a market-based administrative approach/mechanism designed to address the climate change concern and has led to development of an international carbon market. Carbon markets have grown at good pace over the past few years and have facilitated trading of allowances, other carbon instruments and mobilization finance for cleaner technologies. Carbon trading has become a prominent tool for curbing greenhouse gas emissions and the voluntary market has given a critical support in becoming a successful market-based approach for mitigating climate change.

2.3.1. *Carbon emission tracking and reporting*

Carbon mitigation requires truthful disclosure by sources about their carbon emissions. This would help in monitoring regulatory compliance and facilitating emissions trading schemes. Estimating the levels of GHG emissions and removals is an important element of the efforts to achieve this objective. A carbon inventory involves estimation of changes in the stocks of the carbon pools at two different points in time. Carbon emissions are measured in terms of carbon credits where one carbon credit is equal to one tonne of carbon. Standard conversion unit for other green house gases are available to convert it into equivalent CO_2 emission. The unit is written as CO_2-e. Each country under the Kyoto agreement has to declare its own emission. Each country further can regulate the disclosures of carbon emission by the industries. These disclosures can also be voluntary. The carbon emissions appear in databases such as the carbon disclosure project or included as a note to an entity's financial statements. The most widely accepted comprehensive reporting standard with regards to carbon emissions commonly used in practice is the Greenhouse Gas Protocol developed by the World Business Council for Sustainable Development and World Resources Institute (WBCSD 2007). Other registries includes GHG emission reporting program (2004), Climate registry (2008), Montreal climate exchange (2008) etc., have been established to record and track emissions of GHGs. While each regulated program may have its own distinct rules for calculating GHG inventories, there are recognized methodologies to inventory greenhouse gas emissions. There are also recognized methodologies for providing assurance about reported information on greenhouse gas emissions. Some programs require third party verification of GHG emissions reported to governments. ISO has announced and ratified standards for GHG accounting and verification. The ISO 14064 standard for greenhouse gas accounting and verification published on March 2006, provides government and industry with an integrated set of tools for programmes aimed at reducing greenhouse gas emissions, as well as for emissions trading.

2.3.2. *Tradable items in carbon markets*

The tradable items for carbon emission carbon markets use tonnes of "$C0_2$-e" as common denominator for trading. The Kyoto protocol under its emission trading framework, allows the initial sale and trading of the following:

- Permits: Permits are quantity of carbon/GHG emission in metric tonne granted as "allowances" by some authority (say government) to sources of emission. They are called as Assigned Allocation Units (AAUs). The allocation is for a specific year, or could be for any one year after a specific year.

- Credits: Credits are generated by investing into projects for emission reduction at some remote location by the emitters. Credits could be generated either under the Joint Implementation (JI) mechanism or Clean Development Mechanism (CDM) defined by the Kyoto Protocol. Under JI the project for emission reduction can be implemented in developed countries (Annex I countries of Kyoto Protocol) and are called as Emission Reduction Units (ERUs). Under CDM the credits could be generated in the developing countries (Annex I countries of Kyoto Protocol) and are called as Certified Emission Reductions (CERs).

- Derivatives: Derivative trading could be done in two forms as futures and options. In futures, there is a right and obligation to deliver a specified amount, at a specified price, on a specified date. In options there is a right, but not obligation, to buy ('call') or sell ('put') a specified amount, at a specified ('strike') price, during a specified period of time. These two terms are equivalent to stock markets shares and derivatives. In carbon trading, 95% of the trade has been for derivatives, especially in EU and US.

- Removal Unit (RMU): Each RMU is measured as equal to one tonne of CO_2 on the basis of land use, land-use change and forestry activities such as reforestation.

Permits can be seen as disincentive to pollution where as credits can be seen as an incentive to solutions that reduce emissions. Carbon offsets are the credits or permits are the amount of emission reductions that an emitter has achieved in excess of any required reductions. This excess amount can be sold in the market. Kyoto protocol ensures tracking and recording of the transfers and acquisitions of these units in the form of an international transaction log. It has been argued that carbon should be priced highly to create awareness among the consumers as to reduce the use of high carbon producing commodities.

2.3.3. *Climate exchanges*

Carbon exchanges facilitate the trading of carbon credits. They are located in every major geographic region and vary from simple matching of buyer and seller to auction markets and from those limited to European Union Allowances (EUAs) and Kyoto Protocol Certified Emission Reductions (CERs), to those which will soon offer the full range of products from voluntary to mandatory and offer the full range of exchange services: trading, clearing and settlement. Currently there are some 19 carbon exchange initiatives, 11 of which are already in trading. The most significant and widely accepted amongst those are the European Climate Exchange and Chicago Climate Exchange.

Chicago Climate Exchange (CCX)

Chicago Climate Exchange (CCX) established in 2000, is the world's first global greenhouse gas emission reduction and trading system, and the only such system in North America. It was established with the help of Joyce Foundation and then gathered funds from various sectors who worked with Sandor, its founder to develop the core set of rules, protocols and design elements. In 2003, CCX launched trading operations with 13 chartered members. Through their CCX membership, these countries are first to make legally binding commitments to reduce all six greenhouse gas emissions. CCX is a US corporation which is the only emission reduction and trading system for all the six greenhouse gases and only cap and trade system in the whole of North

America. It has nearly 300 members from all sectors worldwide. Reductions made by CCX are the only reductions made in North America through a legally binding compliance regime providing third party verification with FINR.

CCX uses *cap and trade* system (explained in following section) whose members make a legally binding emission reduction commitment. Members are allocated annual emission allowances in accordance with their emissions Baseline and the CCX Emission Reduction Schedule. Members who reduce beyond their targets have surplus allowances to sell or bank; those who do not meet the targets comply by purchasing CCX Carbon Financial Instrument (CFI) contracts.The commodity traded on CCX is the CFI contract, each of which represents 100 metric tons of CO_2 equivalent. CCX issues tradable Carbon Financial Instrument (CFI) contracts to owners or aggregators of eligible projects on the basis of sequestration, destruction or reduction of GHG emissions. CCX emitting Members make a voluntary but legally binding commitment to meet annual GHG emission reduction targets. CFI contracts are comprised of Exchange Allowances and Exchange Offsets. Exchange Allowances are issued to emitting Members in accordance with their emission baseline and the CCX Emission Reduction Schedule. Exchange Offsets are generated by qualifying offset projects.

European Climate Exchange (ECX)

The European Climate Exchange (ECX) is the leading marketplace for trading carbon dioxide emissions, and other GHGs in Europe and internationally. ECX is the only Climate Exchange that complies fully with Kyoto standards.

ECX currently trades EU allowances (EUAs) and CERs (Certified Emission Reduction Credits) and has been doing so since April 2005. Since then, the ECX volumes have grown tremendously. Futures and Options on CERs were introduced in 2008, further cementing ECX's position as the industry benchmark for carbon trading globally. Also, in 2009, two new spot-like contracts were added, the EUA and CER Daily Futures contracts. Statistics show that ECX/ICE Futures is the most liquid, pan-European platform for carbon emissions trading. ECX is operated by the public company Climate Exchange PLC, which also owns the Chicago Climate Exchange.

The underlying commodities being traded at ECX are EU allowances (EUAs) as issued under the EU Emissions Trading Scheme. One EUA equals one tonne of CO_2 (right-to-emit). Approximately 2.3 billion EUAs in total have been granted yearly to the 12,000 energy-intensive installations covered by the EU ETS Directive. ECX added Certified Emission Reduction units (CERs), generated from CDM projects as another underlying commodity.

European Energy Exchange (EEX)

EEX is an exchange under the German Exchange Act and a regulated market within the meaning of MiFID (Markets in Financial Instruments Directive). MiFID is European Union law which provides a harmonised regulatory regime for investment services across the 30 member states of the European Economic Area (the 27 Member States of the European Union plus Iceland, Norway and Liechtenstein). The main objectives of the Directive are to increase competition and consumer protection in investment services.

The participants on the exchange can trade via an open and cost-effective electronic access on equal terms on the energy exchange which boasts the biggest turnover and the highest number of trading participants in Europe. It operates Spot Markets for power, gas and emission rights as well as Derivatives Market on which futures and options on power, gas, emission rights and coal can be traded. EEX has the following executive bodies: the Exchange Council, the Management Board of the Exchange and the Market Surveillance and the Sanctions Committee.

India Climate Exchange (ICX)

Chicago Climate Exchange (CCX) has launched an initiative to establish the first pilot greenhouse gas emissions trading program in India called as the India Climate Exchange (ICX). The goal of this effort is to enable entities in India to become involved in greenhouse gas reductions integrated with emissions trading, for the purposes of climate change mitigation, institution building and social development. Following the example set by CCX, the India Climate Exchange is designed through a consensus process by concerned India-based enterprises, enabling them to determine the most cost effective greenhouse gas mitigation measures, which will in turn, lead to better strategic management of energy costs, new products, and new sources of revenue, job creation and poverty alleviation.

2.4. *Existing mechanisms for carbon trading markets*

The driving force for carbon trading is the relative cost of solutions for emission reduction between two players of the market as discussed earlier. The trading region is normally the area impacted by the pollutant, could be the whole world in case of GHG emission. National or Domestic emissions trading, is carried out within a nationally regulated system to achieve national or domestic emissions targets. The total numbers of allowances or credits are controlled by the national government, but individual transactions within the trading systems are generally not controlled. International trading occurs when multiple countries agree to complementary emissions targets with trading allowed either between countries or between individual firms in different countries.

The carbon market involves players like countries, states, industry etc., those participates voluntarily. Each player is considered to be rational, intelligent and is capable of calculating its own GHG emissions. The carbon markets are established via climate exchanges that provide a platform for trading the carbon credits. Most of the carbon trading happens between the industries. Many different forms of carbon trading markets have evolved over time. Some of them are discussed below.

- **Bubbles:** A player or entity that has multiple emissions sources can combine their total emissions targets under one accounting entity. This will help in using the emission controlling technology to any source that has most cost effective technology, while ensuring the total amount of emissions for the player under required level. This method is called as Bubbles. This method also gives flexibility to the players where the player can decrease emission at some part while increasing it from others, so long as total emissions are equal to or better than previous limits.

- **Offsets or credit-based emission reduction trading:** This type of trading are project-based, often incorporating non-capped industries and entities. This system allows entities that wish to increase their emissions to obtain offsetting reductions from entities that are not required to reduce their emissions. Offsets are created when an emitting company makes voluntary, permanent emission reductions that are legally recognized by a regulator as Emission Reduction Credits or Offsets. Those Offsets are sold to new or expanding emission sources to 'offset' the new emissions. Regulators approve each trade; however, regulators usually require a percentage of the Offsets be retired as a dividend to the environment.

- **Baseline emission reduction trading:** This type of systems are also project-based and allows an entity to voluntarily reduce emissions below an agreed baseline under business as usual. The baseline is calculated as the difference between emission forecast with and without the proposed project. The Clean Development Mechanism (CDM) relies on this mechanism.

- **Rate-based emissions trading**: This system focuses on the emission per unit of output rather than absolute emissions. This system is intended to promote increased efficiency without limiting growth of the underlying business. Within such a system entities that improve their efficiency beyond the target levels can trade the excess improvement with other companies. For example, Corporate Average Fleet Efficiency (or CAFE) standards in the US allow auto manufactures to make changes within their own fleet of vehicles to ensure an overall average improvement in gas mileage per vehicle sold.

- **Cap and trade mechanism:**We describe this mechanism in detail in the following section.

2.4.1. *Cap and trade mechanism*

A cap and trade system [3] is a market-based approach to controlling pollution that allows corporations or national governments to trade emissions allowances under an overall cap, or limit, on those emissions. This mechanism involves two parties, the governing body and the regulated companies or units emitting pollution. The governing body sets a limit on the total amount of CO_2 and other green house gases (equated in terms of CO_2) 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 CO_2 emissions. After the allowances are initially distributed, entities would be free to "trade" any extra credits. Companies that can more efficiently reduce pollution sell permits to companies that cannot easily afford to reduce pollution. The companies that sell the permits are rewarded while those that purchase permits must pay for their negative impact. The cap limits the total amount of allowable emissions, we can lower the cap for stricter environmental standards or rise the cap for addressing the cost issues of reduction. Trading reduces the cost of emission reduction by different distribution across emitters, keeping the overall emission at same level.

An example of a cap and trade mechanism

Let us consider a governing body that wants to reduce the emissions to a level of 30% less than current emission. Assume there are two units (A and B) that are emitting carbon. For simplicity, we consider that each emits 50 units of "$C0_2$-e". Hence the total emission is 100 units and 40% reduction would ensure only 60 units to be emitted by both A and B.

The governing body will now allocate caps to A and B. Let assume it gives equal cap to both i.e. 30 units to each. Let us consider that B can reduce per unit of carbon emission at half the cost A will incur for the same. Hence if B reduced 1 unit of carbon emission at $\$x$ then A will incur a cost of $\$2x$ to reduce the same. Under business as usual (BAU), cost of reduction for A would be $\$40x$ and B would be $\$20x$. The total cost for 6 units of reduction under BAU is $\$60x$.

Let us consider that both A and B agreed for trading the carbon emission. B can always achieve higher levels of reduction (as cost is less) and sell the surplus credits to A. Let B sell 5 units of reduction to A, then the total cost for 40 units of reduction, would be $\$25x$ (cost of B) $+\$30x$ (cost of A) i.e. $\$55x$ and a saving of $\$5x$. Hence using the trading system we can ensure the reductions are achieved at lower cost than the business as usual scenario.

Under the cap and trade mechanism the initial allocation of caps becomes an important issue. After an overall reduction target for emissions is chosen, emissions allowances must be distributed or allocated among emitters. Emitters may later be permitted to trade among themselves, but initial allocations determine who starts with what rights compared to what is required. Basically, there are two main approach for allocation: Auction the allowances or Hand out free allowances to emitters. We describe these briefly below.

Auction

The governing body sells caps or permits to those who submit the highest bids. Typically, each bidder submits a bid reporting the number of units it seeks to buy, and the price it is willing to pay. The auction method follows the principle of polluters paying for the emission. Another benefit of auction is that it treats all the players at the same level and there is no penalty for new players. Also the revenue generated from auction can be reinvested in other pollution reduction initiatives. The drawback is that the emitters dislike paying for pollution rights they previously received for free and it also reduces their ability to invest in technology to reduce emissions.

Under the EU ETS, governments were permitted to auction up to 5% of allowances for the first trading period and up to 10% in the second. Most countries did not auction the maximum percent of auctions but the European Commission has proposed exclusive auctioning of allowances for electricity generators and certain other industrial sectors for the trading period starting in 2013.

The regional Greenhouse Gas Initiative (RGGI), is the first mandatory carbon cap-and-trade program in the United states of America. It covers ten Northeastern and Mid-Atlantic states, and aims to reduce carbon-dioxide emissions below 2009 level by 10 percent by 2018. It has about 225 facilities in the power sector, and is the first mandatory carbon trading program to auction nearly all of its allowances. The compliance period began in January 2009, and there were two pre-compliance auctions in 2008 distributing about 85 percent of allowances.

Free allowances

Under this approach, each firm receives allowances free of charge based on one of the following approaches.

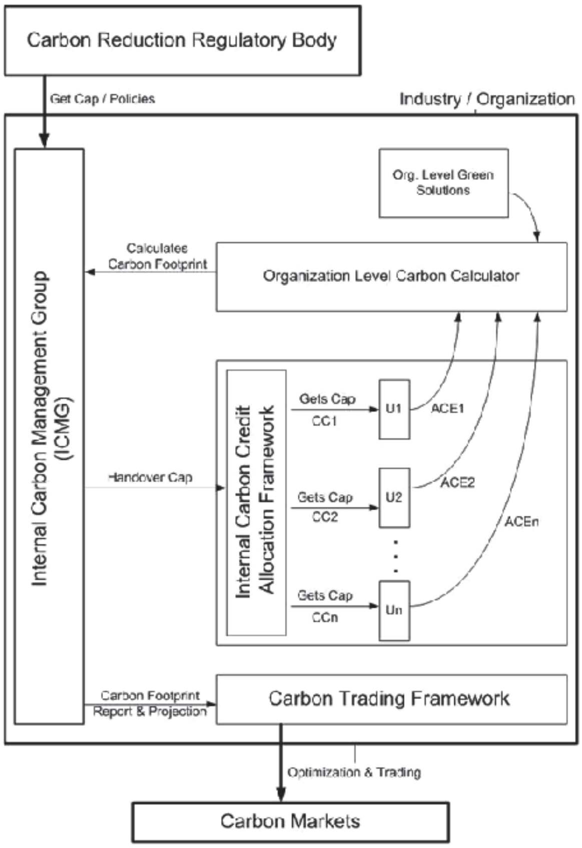
- **Grandfathering**: Here allowances are allocated to emitters based on their past emissions from a baseline period. Grandfathering lets existing firms continue their existing operations without any additional costs but they may need to buy allowances if they seek to expand their operations. This approach imposes lower costs on emission sources as well as to the consumers. However, grandfathering puts new player at a disadvantage.

- **Benchmarking**: In this approach, a regulator assesses each firm's operations including its size and industry. The regulator then estimates a "benchmark" pollution level i.e. how much pollution such a plant should emit, based on analysis of similar emissions elsewhere. If the firm's actual emissions are higher than the regulator's assessment, the firm must buy additional pollution rights; if the firm's actual emissions are lower, it can sell the rights it does not need.

For cap-and-trade systems to work, there must be an accurate and verifiable method of monitoring emissions. At the end of a specified commitment period, an emitter must have allowances equal to or greater than the verified amount of emissions and if it falls short of allowances there should be a strategy for monetary penalty for shortfall. Another case could be where emissions are less than allowances for one commitment period then there should be a strategy for banking of allowances to be used later. Borrowing of allowances would be helpful, if an emitter faces a sudden spike in demand.

Carbon cap-and-trade systems are inherently complex. Similar to the usual fears in stock market, there is always possibility that the prices can be "gamed". In cap-and-trade regime, if the price spikes or tanks, polluters will very likely no longer face the true external costs of their actions. If the price drops as happened in EU ETS industry would be able to pollute even if the external costs are high. Similarly, if the price spikes because of short-term demand as happened in Californian Reclaim system, the regulatory cost would exceed the true external costs. The lack of tracking between trading price and the external harm is the major deficiency of cap-and-trade system. A remedy to this could be to fix a price floor and ceiling that permits trad within a reasonable band, but this may not be acceptable to all players. This flaw in the system has been the USP for groups who want to have carbon tax to be seriously considered. Taxing polluters, may initally make them to simply pay it up, but history has shown that industries work seriously hard to reduce their tax payouts. Further it can be argued that taxing system is a much simpler mechanism, however it may counter argued that tax laws are more often messed up by the government. There is a strong group in the US advocating carbon tax instead of cap-and-trade mechanism to reduce carbon emissions. Cap and Trade is an inclusive mechanism towards emission reduction involving both developed and developing countries, however an inclusive carbon tax framework is difficult to achieve. The majority of the countries participating in the recently concluded Copenhagen meet [4] have rejected the carbon tax concept.

Figure 3: Carbon planning framework for a global industry.



3. Carbon economics problems faced by global industries

As already stated, the entire global community is now involved in undertaking appropriate measures to address issues arising out of climate change and global warming. This is especially true of global industries which fully realize the positive implications of initiating carbon economics programs within the respective companies. We first propose the idea of a company-wide carbon planning framework which would enable a global industry to optimize their carbon footprint.

3.1. *Carbon planning framework*

We propose the following carbon planning process for an organization / industry. We use the word industry from now on to refer to any global industry or organization. An industry comprises multiple divisions that together work toward achieving a common goal. For example a typical Information Technology (IT) company is divided into a number of multiple verticals or divisions. Each vertical caters to either a domain specific client or a business enabler unit. Some examples could be banking domain vertical, internal computer resource vertical, data centers etc.

The framework depicted in Figure 3 takes a case where an industry gets a cap and allocates or distributes the cap to its sub-units. The different blocks in the figure are explained below.

- *Carbon reduction regulatory body*: Usually this is any government approved body outside the jurisdiction of the industry. In case of Cap and trade this body is responsible for calculation and allocation of initial cap. The body also formulating policies for carbon reduction and implements the same.
- *Internal carbon management group (ICMG)*: This is an internal group of an industry or organization. This body gets the cap / policies from the regulatory body. It is responsible for internal allocation of the cap and monitoring the overall carbon emission of the organization / industry. It gets input from the organizations carbon calculator and calculates the excess and shortage of carbon credits organization wide.
- Units/Vertical: Each industry is divided into a finite set of units or verticals, that performs a specific task. In the figure it is shown as (U1, U2, . . . , Un). These units / verticals could be co-located or distributed across geography.

- *Internal Carbon Credit Allocation Framework (ICCAF)*: ICMG uses ICCAF for allocation of carbon cap to individual units / verticals. This framework will use intelligent algorithms for allocating / distributing the cap. Each unit will get cap (CC1, CC2, . . . , CCn) and the carbon calculator will calculate the actual carbon emitted, shown as ACE1, ACE2, . . . , ACEn, by the units at the end of compliance period.
- *Organization level green solutions*: Initiatives taken at the organization level to reduce the carbon emissions.
- *Organization level carbon calculator*: This calculator will calculate the carbon emission across the organizations and reports back to the ICMG.
- *Carbon markets*: The marketplace for selling and buying carbon credits. It includes regulated and unregulated markets.
- *Carbon trading framework*: This framework will use intelligent algorithms to optimize carbon trading. The trading could involve buying (in case of shortage of credits to meet the cap), selling (in case of excess credits saved), or both.

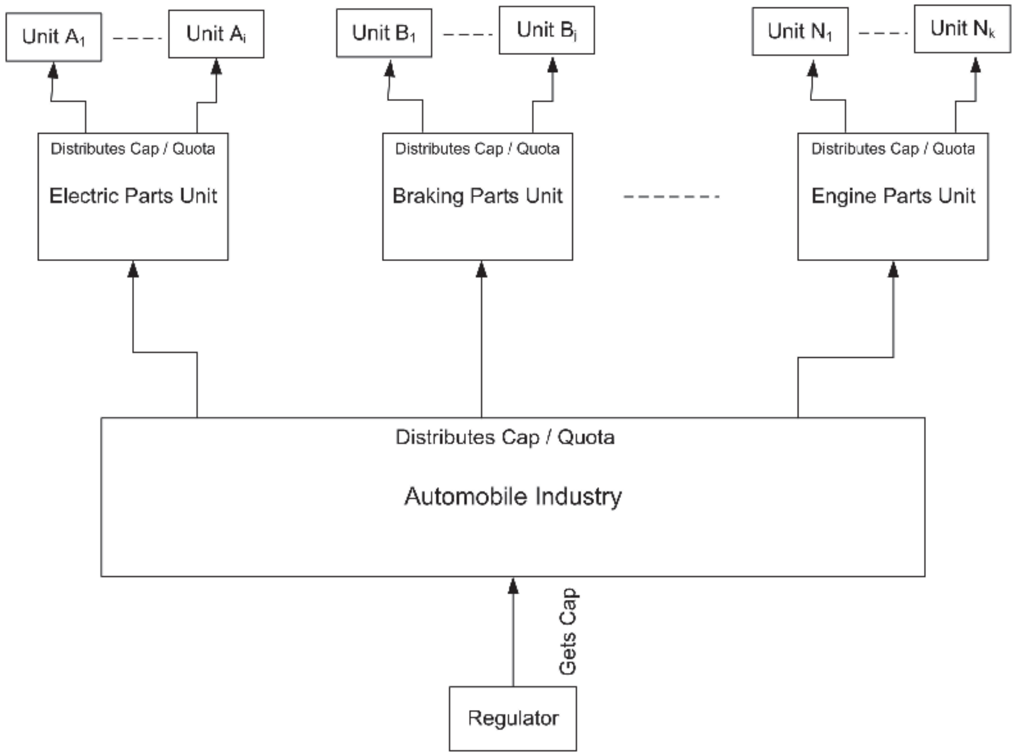
The framework described above provides a systematic way of handling the carbon footprint optimization problem in any industry or organization. We will now focus on four important problems that are a part of the above framework. These are: carbon credit allocation, carbon credit buying, carbon credit selling, and carbon credit exchanging. We elaborate upon these four problems below.

3.2. *Carbon Credit Allocation (CCA)*

Under the Kyoto protocol, each Annex I country gets a cap on its emission. Usually the country would be emitting more emissions than the cap and hence have to reduce the emission and bring it to a level equivalent to the cap. To achieve this the country may want to distribute this reduction among its organizations / industries by imposing subsequent caps on their emission. Further an industry that gets a cap, would in turn like to distribute the reduction it has to make to its divisions. Since carbon reductions incur a cost, the CCA problem seeks to distribute the carbon reduction units in a way that the total cost of reduction is minimum.

Let us consider a company having its emission level at *E* units. The company obtains a cap from a regulatory body and is required to keep its emission

Figure 4: Structure of a typical automobile industry.



level to C units where $C < E$. Now the company has to make efforts to reduce $M = (E - C)$ units of emission. The efforts to reduce emission will incur some cost. The objective here is to distribute M to achieve minimum cost. Let the company have n divisions. These divisions could be either internal i.e., within the company or external (outsourced to partners or ancillary units). For example, Figure 4 shows the structure of a typical automobile industry. The M carbon reduction units have to be distributed among these divisions.

Each division would incur some cost in achieving a certain amount of emission reduction. The individual divisions have to precisely estimate their cost functions for their emission reductions. Each division has its own cost function that describes the cost as a function of number of emission units to be reduced. The cost functions of individual divisions are typically private information of the divisions.

We consider each division to be independent, autonomous entity and we assume that these units are motivated and geared towards undertaking reduction in carbon emissions. The division may or may not report the true cost function when asked to do so by a social planner such as the planning division in the company. If the cost functions are all known to the social planner in a deterministic way, the social planner only needs to formulate an appropriate optimization problem whose solution would achieve the objective of distributing M reduction units among the n divisions so as to minimize the total cost. However, if the cost functions are not known truthfully, the social planner has the additional problem of first eliciting the cost functions first and then solving an optimization problem. This is where mechanism design becomes useful.

Figure 5 provides a conceptual picture of the carbon credit allocation problem. Suppose each division bids a non-decreasing, convex cost curve $F_i(x)$. Mathematically,

$$\text{Minimize} \sum_i F_i(x_i)$$

$$\text{subject to} \sum_i x_i \geq M, i = 1, \ldots, n$$

$$x_i \geq 0, i = 1, \ldots, n.$$

Let B be the budget available to the company to perform carbon reduction. Now the problem turns out to be one of maximizing the number of carbon credits that can be reduced by the company by allocating them to its divisions. Another optimization problem that can be formulated in the carbon allocation setting is to find if the company can reach the reduction target for a given budget B and if it cannot, the problem is to find out the extent to which the company can distribute the carbon reductions among its divisions. Mathematically,

$$\text{Maximize} \sum_i x_i$$

$$\text{subject to} \sum_i F_i(x_i) \leq B, i = 1, \ldots, n$$

$$x_i \geq 0, i = 1, \ldots, n.$$

The above problem formulations assume that the individual divisions truthfully report their cost

Figure 5: Carbon credit allocation problem.

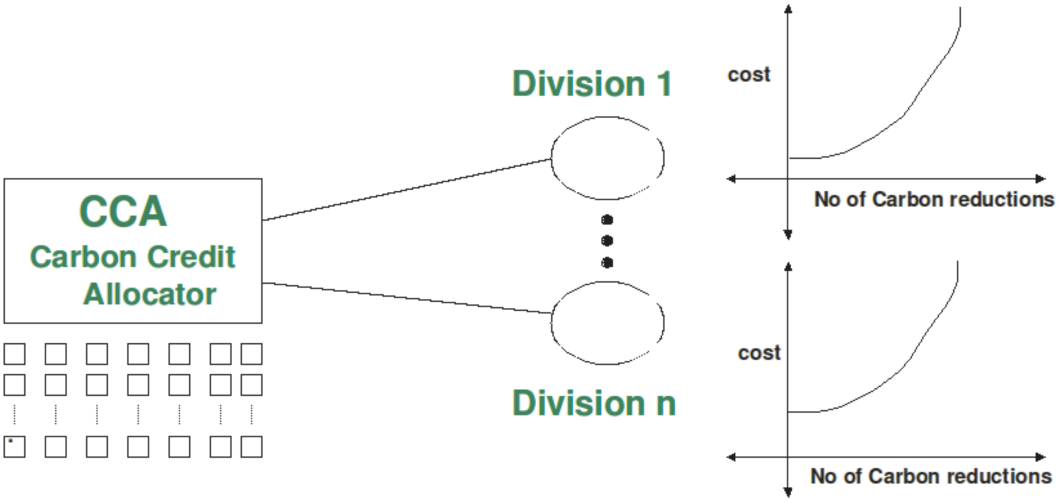
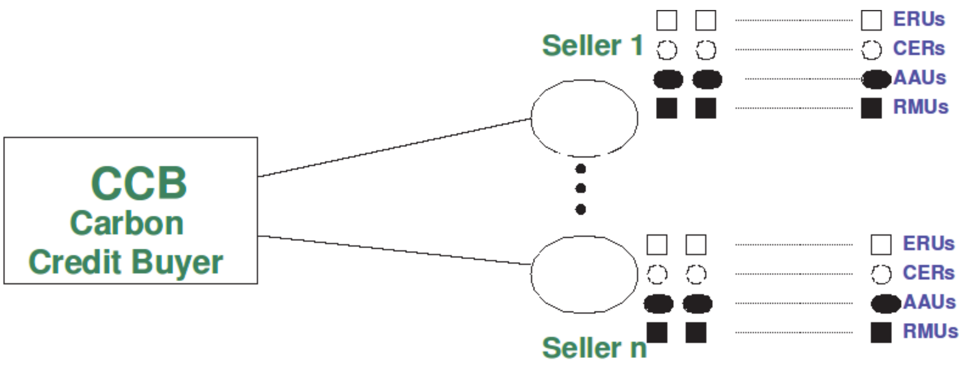


Figure 6: Carbon credit buying problem.



curves. If they do not report their cost functions truthfully, we will have to invoke mechanism design techniques.

3.3. *Carbon Credit Buying (CCB)*

A carbon footprint is the vector of emissions of greenhouse gases caused by an organization, event, or product. The carbon footprint can be erased by buying carbon credits/offsets. The basic idea of a carbon offset is to figure out the personal contribution level to the global warming problem from such activities as driving, flying, or home energy use. This purchase of carbon offsets funds reductions in greenhouse gas emissions through projects such as wind farms, which produce clean energy that displaces energy from fossil fuels.

Consider a business that owns a factory putting out 100,000 tonnes of greenhouse gas emissions in a year. Let the government be an Annex I country that enacts a law to limit the emissions that the business can produce. Suppose the factory is given a quota of say 80,000 tonnes per year. The factory either has to reduce its emissions to 80,000 tonnes or is required to purchase carbon credits to offset the excess. After costing up alternatives the business may decide that it is uneconomical or infeasible to invest in new machinery for that year. Instead it may choose to buy carbon credits on the open market from organizations that have been approved as being able to sell legitimate carbon credits.

Figure 6 provides a conceptual picture of the carbon credit buying problem. An industry (carbon credit buyer) may be interested in buying a certain quantity of ERUs, CERs, AAUs, and RMUs. There could be sellers of these units in the open market. The prices quoted by the sellers may or may not be the true prices of these units. So, we need to use techniques of mechanism design to design a procurement mechanism that would be acceptable to the buyer and the sellers.

3.4. *Carbon Credit Selling (CCS)*

Smaller companies can earn revenue by selling carbon credits to large companies that produce a large volume of pollution. Thus, businesses that are involved in reducing carbon emissions or who produce low emissions in general can sell carbon credits on some exchanges like the Chicago Climate Exchange. Businesses that may be able to sell carbon credits include farms, logging companies, solar power businesses, and any company or business that produces low carbon emissions.

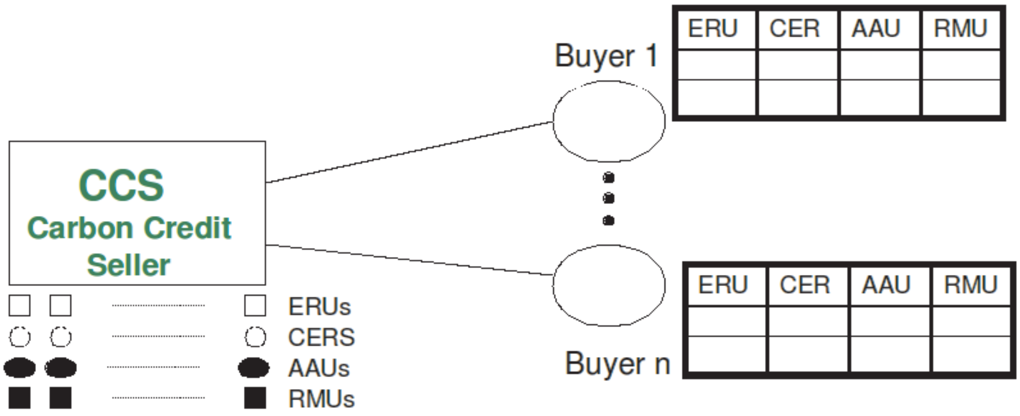
Figure 7 provides a conceptual picture of the carbon credit selling problem. An industry (carbon credit seller) may be interested in selling surplus quantities of ERUs, CERs, AAUs, and RMUs. There could be buyers of these units in the open market. The prices quoted by the buyers may or may not reflect the true valuations the buyers have for these units. So, we need to use techniques of mechanism design to design a selling mechanism that would be acceptable to the buyer and the sellers.

3.5. *Carbon Credit Exchange (CCE)*

We have considered one-sided auctions where in only buyers/sellers are interested in buying/selling the carbon credits. Two-sided, or double auctions permit multiple buyers and sellers to trade carbon credits.

Figure 8 provides a conceptual picture of the carbon credit exchange problem. Several industries (carbon credit sellers) may be interested in selling surplus quantities of ERUs, CERs, AAUs, and RMUs. There could be several industries (carbon credit buyers) interested in procuring these units. The prices quoted by the sellers and the buyers may or may not reflect the true valuations they have for these units. So, we need to use techniques of mechanism design to design a exchange mechanism that would be acceptable to the buyers and the sellers.

Figure 7: Carbon credit selling problem.



4. Mechanism design

The four carbon economics problems mentioned above are essentially decision or optimization problems with incomplete information. More specifically, we have the following characteristics.

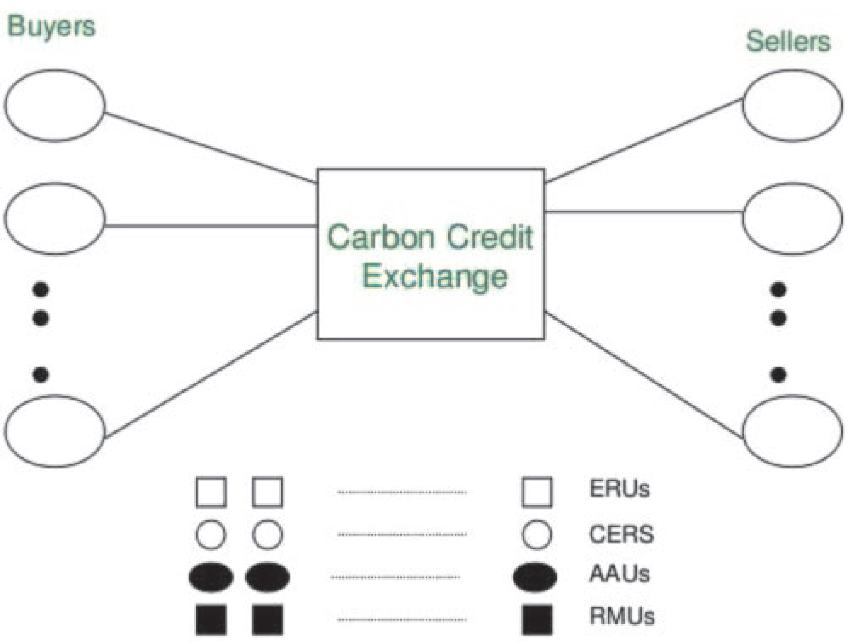
- There is a set of decision makers or players who interact in a strategic way. The players have well defined payoff functions. They are rational in the sense of striving to maximize their individual payoffs. The objectives of the individual players could be conflicting. Both conflict and cooperation are possible during the interactions of the players.
- Each player holds certain information which is private 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 an equilibrium of the induced game, the desired system wide solution is implemented. Mechanism design provides the process for such reverse engineering of games.

The theory of *mechanism design* is concerned with settings where a policy maker (or social planner) 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. Mechanism design theory uses the framework of *non-cooperative games with incomplete information* and seeks to study how the privately held preference information can be elicited. The theory also clarifies the extent to which the preference elicitation problem constrains the way in which social decisions can respond to individual preferences. In fact, mechanism design can be viewed as *reverse engineering* of games or equivalently as the *art of designing the rules of a game to achieve a specific desired outcome*. The main focus of mechanism design is to design institutions or protocols that satisfy certain desired objectives, assuming that the individual agents, interacting through the institution, will act strategically and may hold private information that is relevant to the decision at hand.

Mechanisms have been used and practiced from times immemorial. Auctions provide a popular example of mechanisms; as is well known, auctions have been in vogue for a long time for selling, procuring, and exchanging goods and services. A simple, popular example captures the idea behind mechanisms quite strikingly. The example is that of a mother of two kids who has to design a mechanism to make her two kids share a cake equally. The mechanism she designs is the following: (1) One of the kids would slice the cake into two pieces and (2) the other kid would pick up one of the pieces, leaving the remaining piece to the kid who sliced the cake into two pieces. This mechanism implements

Figure 8: Carbon credit exchange problem.



the desirable outcome of the two kids sharing the cake equally (of course, it would be interesting to see what a suitable mechanism would be if instead of two, there were more kids).

4.1. *Mechanism design: A brief history*

Leonid Hurwicz (Nobel laureate in Economic Sciences in 2007) first introduced the notion of mechanisms with his work in 1960 [5]. He defined a mechanism as a communication system in which participants send messages to each other and perhaps to a *message center* and a pre-specified rule assigns an outcome (such as allocation of goods and payments to be made) for every collection of received messages. William Vickrey (Nobel laureate in Economic Sciences in 1996) wrote a classic paper in 1961 [6] which introduced the famous Vickrey auction (second price auction). To this day, the Vickrey auction continues to enjoy a special place in the annals of mechanism design. John Harsanyi (Nobel laureate in Economic Sciences in 1994 jointly with John Nash and Richard Selten) developed the theory of games with incomplete information, in particular Bayesian games, through a series of three seminal papers in 1967–68 [7–9]. Harsanyi's work later proved to be of foundational value to mechanism design. Hurwicz [10] introduced the key notion of incentive compatibility in 1972. This notion allowed mechanism design to incorporate the incentives of rational players and opened up mechanism design. Clarke [11] and Groves [12] came up with a generalization of the Vickrey mechanisms and helped define broad class of dominant strategy incentive compatible mechanisms in the quasi-linear environment.

There were two major advances in mechanism design in the 1970s. The first was the *revelation principle* which essentially showed that direct mechanisms are the same as indirect mechanisms. This meant that mechanism theorists needed to worry only about direct mechanisms, leaving the development of real-world mechanisms (which are mostly indirect mechanisms) to mechanism designers and practitioners. Gibbard [13] formulated the revelation principle for dominant strategy incentive compatible mechanisms. This was later extended to Bayesian incentive compatible mechanisms through several independent efforts [14] — Maskin and Myerson (both Nobel laureates in Economic Sciences in 2007) had a leading role to play in this. In fact, Myerson developed the revelation principle in its greatest generality [14]. The second major advance in mechanism design in the 1970s was on *implementation theory* which addresses the following problem: can a mechanism be designed so that all its equilibria are optimal? Maskin [15] gave the first general solution to this problem.

Mechanism design has made phenomenal advances during 1980s, 1990s, and during the past few years. It has found widespread applicability in a variety of disciplines. These include: design of markets and trading institutions [14,16,17], regulation and auditing [14], social choice theory [14], and computer science [18]. The above list is by no means exhaustive.

4.2. *Mechanism design framework*

Designing a mechanism can be viewed as a problem of designing a *game with incomplete information* having an equilibrium in which the required social choice function is implemented.

Consider a set of agents or players $N = \{1, 2, \ldots, n\}$ with agent i having a type set Θ_i $(i = 1, 2, \ldots, n)$. The type set of an agent represents the set of perceived values of an agent (also called private values). For example, in an auction, the type of an agent may refer to the valuation that the agent has for different items up for auction. The two most common models of valuation used in the context of auction design are: *independent-private-values model* and *common-value model* [19]. In the *independent-private-values-model*, each bidder knows precisely how much she values the item. She does not know the valuations of other bidders for this item but perceives any other bidder's valuation to be a draw from a probability distribution. Also, she knows that the other bidders regard her own valuation as being drawn from a probability distribution. In the *common-value model*, the item being auctioned has a single objective value but nobody knows its true value. The bidders, having access to different information sources, have different estimates of the item's valuation.

Let Θ be the Cartesian product of all the type sets of all the agents (that is Θ is the set of all type profiles of the agents). Let X be a set of outcomes. An outcome, in the context of auctions, corresponds to an assignment of auction items to bidders and the payments to be made to or received by the bidders. A social choice function is a mapping from Θ to X and associates an outcome with every type profile. A social choice function in an auction corresponds to a desirable way of producing outcomes from given type profiles. Let S_i denote the action set of agent i, that is S_i is the set of all actions that are available to an agent in a given situation. A strategy s_i of an agent i is a mapping from Θ_i to S_i. That is, a strategy, $s_i(\theta_i)$ maps, each type of an agent to a specific action the agent will choose if it has that type. In an auction, a strategy corresponds to the bid the agent will place based on its observed type. Let S be the Cartesian product of all the strategy sets. A mechanism μ is basically a tuple $(S_1, S_2, \ldots, S_n, g(.))$, where g is a mapping from S to X. That is, $g(.)$ maps each strategy profile into an outcome. A given mechanism can always be associated with a game with incomplete information, which is called the game induced by the mechanism.

We say that a mechanism $\mu = (S_1, S_2, \ldots, S_n, g(.))$ implements a social choice function f if there is an equilibrium strategy profile $(s_1^*(.), s_2^*(.), \ldots, s_n^*(.))$ of the game induced by μ such that, for all possible type profiles $(\theta_1, \theta_2, \ldots, \theta_n)$,

$$g(s_1^*(\theta_1), s_2^*(\theta_2), \ldots, s_n^*(\theta_n)) = f(\theta_1, \theta_2, \ldots, \theta_n).$$

That is, a mechanism implements a social choice function $f(.)$ if there is an equilibrium of the game induced by the mechanism that yields the same outcomes as $f(.)$ for each possible profile of types. Depending on the type of equilibrium we qualify the implementation. Two common types of implementations are *dominant strategy implementation* and *Bayesian Nash implementation*, corresponding respectively to *weakly dominant strategy equilibrium* and *Bayesian Nash equilibrium*. The weakly dominant strategy equilibrium is an extremely robust solution concept that ensures that the equilibrium strategy of each agent is an optimal strategy regardless of the strategies of the rest of the agents. The Bayesian Nash equilibrium is a weaker solution concept that only guarantees that the equilibrium strategy of each agent is optimal with respect to the equilibrium strategies of the other agents. For a detailed discussion of these, the reader is referred to [1,20].

A *direct revelation mechanism* corresponding to a social choice function $f(.)$ is a mechanism of the form $\mu = (\Theta_1, \Theta_2, \ldots, \Theta_n, f(.))$. That is, the strategy sets are the type sets itself and the outcome rule $g(.)$ is the social choice function itself. A social choice function is said to be incentive compatible in dominant strategies (or strategy proof or truthfully implementable in dominant strategies) if the direct revelation mechanism μ implements $f(.)$ in a weakly dominant strategy equilibrium where the equilibrium strategy of each agent is to report its true type. Similarly a social choice function is said to be Bayesian Nash incentive compatible if the direct revelation mechanism μ implements $f(.)$ in a Bayesian Nash equilibrium where the equilibrium strategy of each agent is to report its true type. The *revelation principle* [1,20] states that if a social choice function can be implemented in dominant strategies (or in Bayesian Nash equilibrium), it can also be truthfully implemented in dominant strategies (or in Bayesian Nash equilibrium). The revelation principle enables one to focus attention only on incentive compatible mechanisms.

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 procurement auctions) are described next [1,20,21].

4.3. *Mechanisms: desirable properties*

We now present an intuitive discussion of properties that an auction designer looks for while designing an auction mechanism. For a detailed treatment of these, the reader is referred to [1,20].

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*, *weakly dominant strategy equilibrium*. It can be seen that weakly dominant strategy equilibrium is special case of Nash equilibrium and Nash equilibrium is special case of Bayesian Nash Equilibrium.

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 [20,1]), Pareto efficiency implies allocative efficiency.

Incentive compatibility

A mechanism is said to be incentive compatible if the it is a 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 the each agent finds it optimal to report its true valuation irrespective of what the other agents report. BIC on the other hand means that the 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 the strategies of the other agents.

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 not participated in the mechanism. That is, every agent gains a non-negative utility by participating in the mechanism.

Budget balance

A mechanism is said to be *weakly* budget balanced if the sum of monetary transfers between the buyer and the sellers is non-negative, 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.

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.

Solution stability

The solution of a mechanism is stable, if there is no subset of agents that could have done better, coming to an agreement outside the mechanism.

Low transaction costs

The buyer and sellers would like to minimize the costs of participating in auctions. Delay in concluding the auction is also a transaction cost.

Fairness

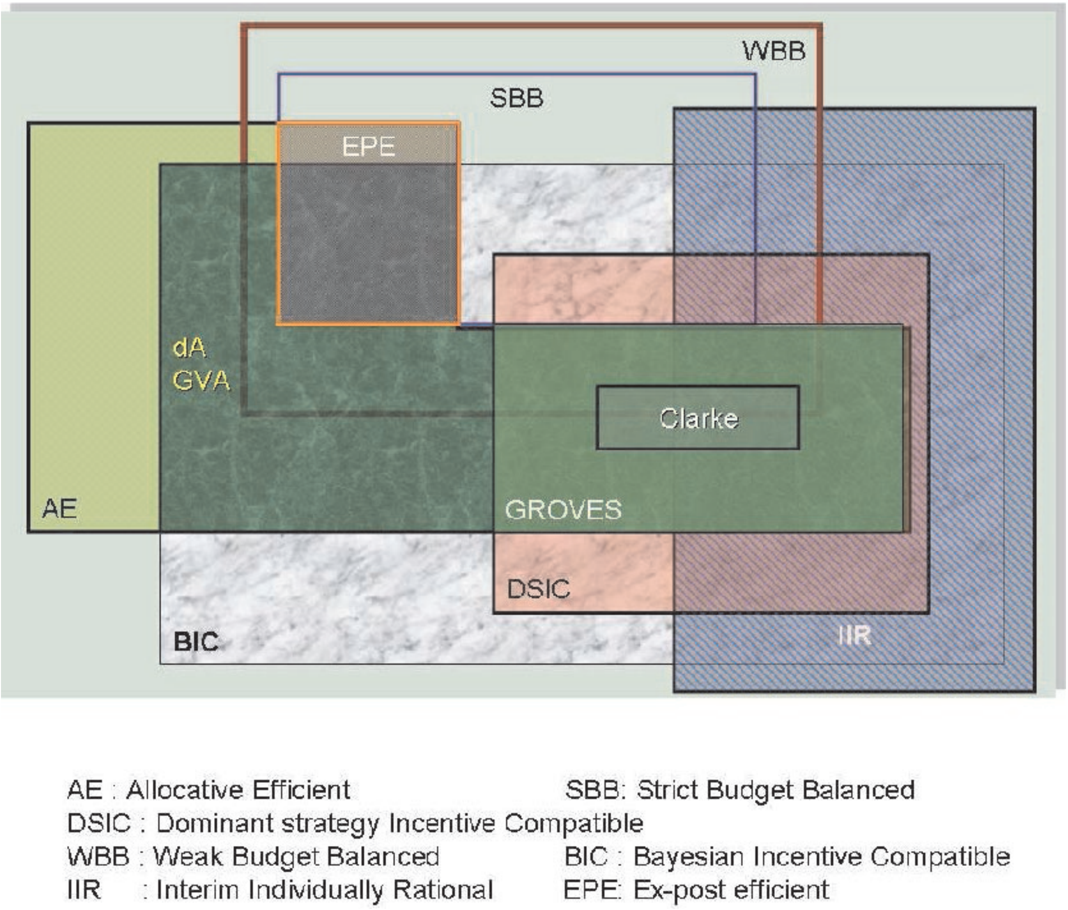
Winner determination algorithms, especially those based on heuristics, could lead to different sets of winners at different times. Since there could be multiple optimal solutions, different sets of winners could be produced by different algorithms. This creates a perception of unfairness and can influence bidders' willingness to participate in auctions. Bidders who lose even though they could have won with a different algorithm could end up feeling unfairly treated.

4.4. *Design space for mechanisms*

Ideally, one would like to put in place an auction mechanism that satisfies all the properties described above, while simultaneously achieving computational tractability. Unfortunately this is in the realm of impossibility, as shown by several landmark results in mechanism design theory which rule out the possibility of mechanisms simultaneously satisfying certain combinations of properties. Fortunately, there do exist certain combinations of properties which can be simultaneously satisfied. We indicate below some of the important results germane this.

- Arrow [1,20] first pointed out the impossibility of implementing a Pareto efficient social choice function unless it is *dictatorial* (a dictatorial social choice function is a very special type of social choice function that requires the presence of a distinguished agent such that the function always chooses a top ranked outcome of this agent). The Gibbard–Satterthwaite theorem [1,20] is also similar in spirit to Arrow's theorem. These impossibility results are in the context of settings where the agents simply have ordinal preferences over outcomes.
- However, when we are in quasi-linear settings (where the preferences may be captured by utility functions and furthermore utilities are comparable across agents), it was shown by Groves [12] and Clarke [11] that allocatively efficient and strategy proof mechanisms are possible. These mechanisms are known by the name *VCG mechanisms*. Clarke's mechanisms are in fact a special class of Groves mechanisms. The GVA (Generalized Vickrey Auction) mechanism is basically the Clarke mechanism applied to the case of combinatorial auctions. The famous Vickrey auction is a special case of the Clarke mechanism applied to the case of auction of a single indivisible item.

Figure 9: Design space of mechanisms.



- The Groves mechanisms are in general not budget balanced even in quasi linear settings. There are two useful settings where they do satisfy budget balance.
  - The first setting arises when the type information of one of the agents is completely known or when the agent does not have any preferences over the allocations. In this setting, by defining monetary transfers appropriately, we can achieve the strategy proof property, allocative efficiency, and weak budget balance. The GVA mechanism is an example of one such situation. In fact, the GVA mechanism satisfies four properties simultaneously: allocative efficiency, individual rationality, weak budget balance, and strategy proofness.
  - The second setting arises when we settle for the weaker notion of Bayesian Nash equilibrium, as opposed to the much stronger dominant strategy equilibrium. In this setting, it was shown by Arrow and d'Aspremont and Gerard-Varet [1, 20] that, under quasi-linear preferences, it is possible to have a mechanism (which is called the dAGVA mechanism) that is allocatively efficient, Bayesian Nash incentive compatible, and budget balanced.
- The positive result indicated in the second setting above may not however be sustained when we insist on individual rationality. The Myerson–Satterthwaite [1,20] theorem articulates this negative result: Even in the simplest of trading situations such as in a bilateral trade (a simple exchange setting), it is impossible to design a social choice function or a mechanism that is incentive compatible, allocatively efficient, budget balanced, and individually rational.
- Myerson [22] showed that revenue maximization, individual rationality, and Bayesian incentive compatibility can be achieved simultaneously if we sacrifice allocative efficiency. However, this result is true only while auctioning a single indivisible item.

The space of mechanisms can be diagrammatically represented as in Figure 9. This figure clearly captures the challenge involved in designing a mechanism or an auction that satisfies a desired combination of properties. For more details on these results, we refer the reader to [1,20]. The above discussion gives an idea of how the design space for auctions is constrained.

Another key factor that constrains the design space further is the computational complexity at the agent level and at the mechanism level. The central problem of an auction designer is to devise the best possible mechanism that is contained in this constrained design space and that is computationally tractable.

4.5. *Computational complexity issues in mechanism design*

In an economic mechanism where resource allocation is based on decentralized information, computations are involved at two levels: first, at the agent level and secondly at the mechanism level. The complexity questions involved are briefly indicated below. For a more detailed discussion refer to [23].

Complexity at the agent level

- *Valuation complexity*: How much computation is required to provide preference information within a mechanism? For instance, in a multi-item procurement scenario where the items exhibit cost complementarities, estimating a bid for every possible permutation of the bundle of items is costly.

- *Strategic complexity*: Should agents model other agents and solve game theoretic problems to compute an optimal strategy? For instance, in a sealed bid procurement contract scenario, sellers will need to not only take their valuation of the contracts into consideration but also the bidding behavior of their competitors. This requires sophisticated computational capability. The strategic complexity involves, valuation complexity. However, even if agents have an oracle access to valuations, agents have to face strategic complexity.

Complexity at the mechanism level

- *Winner determination complexity*: How much computation is expected of the mechanism infrastructure to compute the winning agents given the bid information of the agents. It turns out in many common auction problems that the winner determination problem is NP-hard [23,24].

- *Payment determination complexity*: How much payment do the winners of an auction make or receive? In many situations, determining the price or payment also turns out to be an NP-hard problem [23].

- *Communication complexity*: How much communication is required between agents and the mechanism to compute an outcome. For instance, in an English auction, where individual valuations are revealed progressively in an iterative manner, the communication costs could be high if the auction were conducted in a distributed manner over space and/or time.

The point to be noted is that even if we are able to design a mechanism that satisfies many desired properties, the computational complexity at the mechanism level and at the agent level may prohibit the use of this mechanism. An example here is that of GVA applied to multi-item procurement auctions. GVA satisfies allocative efficiency, weak budget balance, strategy proofness, and individual rationality. However, the winner determination problem turns out to be a set covering problem which is NP-hard. The payment determination problem is also a set covering problem. In fact, the payment determination problem is to be solved for each winner separately!

4.6. *A review of relevant literature*

There have been sporadically some papers in the literature which have reported the use of game theory and less frequently mechanism design to problems in environmental economics in general and and carbon economics in particular. We present a very brief review below.

The papers by Barrett [25–27] have analyzed the role of transfers in a compliance model stressing the role of renegotiation-proof strategies and also analyzed International Environmental Agreements (IEAs) using a membership and a compliance model and compared both approaches. The paper by Bennett et al [28] has analyzed issue linkage with a compliance model providing many examples. The book by Bloch [29] has presented an important overview article on novel coalition concepts with examples of industrial economics, trade theory and IEAs. Carraro [30] has introduced several new coalition concepts for the analysis of IEAs. Botteon and co-authors [31] report an empirical study analyzing IEAs with a membership model stressing the role of transfers for the success of cooperation. Cesar and co-authors [32] have analyzed issue linkage with a compliance model stressing the role of mirror asymmetries of issues for the success of issue linkage. Finus and co-authors [33] [34] have analyzed issue linkage with a membership model focusing on the link between a trade agreement and an IEA and applied coalition concepts to the analysis of IEAs.

Finus [35] has written a book on game theory and cooperation on environmental issues. This book covers important topics such as: (1) Issue linkage in compliance models (2) Renegotiation-proof strategies in compliance models (3) Classical concepts of membership models (internal and external stability and core) and (4) Coalition formation analyzed with a compliance model. Finus [36] has also written an overview article on game theory and IEAs, providing a critical analysis of the applicability of game theoretical results for policy recommendations.

Folmer and co-authors [37] have some interesting results on a game theoretical analysis of IEAs. The paper by Parkash et al [38] offers a scheme for sharing national abatement costs through international financial transfers, assuming a simple economic model of transfrontier pollution. However, the solution is not robust against free riding of the emitting entities not interested in the agreement. Also, the cost functions are assumed to be linear.

The article by Kronbak and Lindroos [39] studies cooperative sharing rules in fisheries coalition games and develops a new sharing rule which takes into account the stability of cooperation when externalities are present. However the model discussed in this paper is restricted to three players.

A complete theoretical characterization is provided by Dutta and Radner [40,41] for characterizing the best equilibrium when the global warming process is modeled as a dynamic commons game, in which the players are countries. They argue that, in the absence of a world government, an effective treaty to control the emissions of greenhouse gases should be self-enforcing. A self-enforcing treaty has the property that, if a country expects other countries to abide by the treaty, it will be in the self-interest of that country to abide by the treaty too. A self-enforcing treaty can be modeled as a Nash equilibrium of a suitably defined dynamic game among a large number of sovereign countries of diverse sizes and economic capabilities. They have studied such a game and characterized its equilibria and the global-Pareto-optimal solutions and identified one of the equilibria, called as *business as usual*, with the current situation. The multiplicity of equilibria in the game provides an opportunity to move from the inefficient business-as-usual equilibrium to one or more equilibria that are Pareto-superior.

Maskin and Baliga [42] have suggested some mechanisms for the environment, however assuming the cost per unit reduction to be equal to one unit. They have shown that any pareto-efficient agreement involving two or more communities is vulnerable to free-riding. Hence, some kind of government intervention is called for. The simplest intervention is for the government to impose a Pareto-efficient vector of quotas $(q_1, \dots q_N)$, where for each j, community j is required to reduce pollution by at least the amount q_j. Another intervention by the government is to set a vector of subsidies $(s_1, \dots, s_N)$, where for each j, community j is paid s_j for each unit by which it reduces pollution. Both these solutions are studied in two information environments where preference profile is verifiable by the government (complete information) and not verifiable (incomplete information). It is observed that a social choice function entailing Pareto-efficient pollution reduction cannot be implemented in dominant strategy equilibrium if it is balanced (the money transfers sum to zero). However, they have shown that relaxing the notion of implementability from dominant strategy to Bayesian equilibrium permits the implementation of balanced social choice functions. However, the construction of the expected Groves mechanism requires the common knowledge of distribution of type sets which is infeasible.

5. Mechanisms for carbon credit allocation

We present here some mechanisms in the context of carbon credit allocation, taking the perspective of a global industry. As discussed in Section 3, let M denote the number of carbon credit reductions to be made by the company and let there be n divisions. The carbon planning department in the industry then asks from each division bids specifying cost curves from each division. The bid from each division could be assumed to be a non-decreasing, convex cost function similar to that shown in Figure 2.

Each bid can be represented as a vector of tuples (x_{ij}, p_{ij}) where $(x_{ij} - x_{i(j-1)})$ is the number of carbon credits that can be reduced by division i at a per unit reduction cost of p_{ij}. For example, a bid $((50,4),(100,7),(150,21)(200,27),(250,38))$ would mean the following. The per unit cost of reduction if the number of carbon credits to be reduced is less than or equal to 50 is 4. If the number to be reduced lies between 51 and 100, then the first 50 units have a per unit reduction cost of 4 while the next 50 unit reductions will have a per unit cost of 7, etc. The total cost of reduction for, say, 160 units will be $50 \times 4 + 50 \times 7 + 10 \times 21$, which is equal to 760. Consider each tuple as an item with weight $(x_{ij} - x_{i(j-1)})$ and cost p_{ij}. We are required to select a set of tuples such that the sum of the weights of all the tuples in the set is at least M and the total cost is minimum. Mathematically,

$$\text{Minimize} \sum_i \sum_j (x_{ij} - x_{i(j-1)}) p_{ij}$$

$$\text{subject to} \sum_i \sum_j (x_{ij} - x_{i(j-1)}) \geq M$$

$$a_i \leq \sum_j (x_{ij} - x_{i(j-1)}) \leq b_i, i = 1, \dots, n.$$

In the above, a_i specifies a lower bound and b_i specifies an upper bound on the number of carbon credit reductions required from division i. The lower bound captures the minimum number of carbon credit reductions mandated from the division and the upper bound reflects the carbon credit reduction capacity of the division. As discussed in Section 3.2, the divisions could be either external or internal to the industry. The divisions could potentially be independent and autonomous organizations within the global company. The cost functions are typically private information of the divisions. The carbon planning department is required to elicit this information that is privately held by the divisions. We consider two broad scenarios: (a) Divisions are honest and report their cost functions truthfully (b) Divisions are strategic and will report their cost functions truthfully only if there is an appropriate incentive to do so.

5.1. *Allocation when the divisions are honest*

We first assume that all the divisions truthfully report their cost functions. We present a simple algorithm (which is a modified version of the algorithm used in [43] to our setting) to obtain an optimal allocation of carbon credit reductions.

- Set initial cost to zero.
- Sort the tuples in ascending order of their per unit reduction costs. In the case of duplicates, arrange in the ascending order of the size of the tuple $(x_{ij} - x_{i(j-1)})$.
- It can be seen that the problem is similar to a knapsack problem [43]. Pick the tuples in the above order and fill the knapsack. Cost is incremented by the total 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 compute the cost accordingly.
- Return the the total cost.

The final cost returned by the algorithm is the total cost that is incurred by all the divisions in achieving the carbon reduction. The cost incurred by each division depends upon the allocation. We provide the following example to illustrate the above algorithm.

Example 5.1. *Let the company be interested in procuring 200 carbon reductions 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 above algorithm. We get $k = \langle 100,50,50,0\rangle$ *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. Total cost incurred in performing the reduction is* $550+350+800 = 1700$.

If there does not exist any allocation that costs less than the above allocation, then the above is optimal. In fact, the above algorithm gives a minimum cost solution as proved in [44]. If k is the maximum number of tuples among all the preferences, then the total running time of the above algorithm is $O(kn)$.

5.2. *Allocation when the divisions are strategic*

Consider the situation when the divisions are self-interested and may not reveal their cost curves truthfully unless an appropriate incentive is offered. This entails the use of a suitable mechanism to solve the allocation problem. There are many different mechanisms that could be used in this context depending on the properties required. We have already seen several properties that are relevant, such as:

- Incentive compatibility
  - DSIC (dominant strategy incentive compatibility): Each division finds it a best response to reveal its true cost curve, irrespective of what is reported by the other divisions.
  - BIC (Bayesian incentive compatibility): Each division finds it a best response to reveal its true cost curve, whenever other divisions also report their true cost curves.
- *Allocative Efficiency* (AE): The company allocates the carbon reductions to the divisions so as to minimize the total cost incurred by the company for achieving the reduction.
- *Individual Rationality* (IR): The divisions voluntarily participate in the carbon reduction program since the mechanism is such that they always gain non-negative utilities by participating.
- Budget Balance (BB):
  - WBB (weak budget balance): The total amount received by the social planner is greater than or equal to the total amount paid by the social planner.
  - SBB (strong budget balance): The total amount received by the social planner is exactly equal to the total amount paid by the social planner.
- Cost minimization: The total cost of achieving the required amount of carbon credit reduction is minimal.

We first present a simple solution based on the the well known class of VCG mechanisms [1]. In particular we present a solution based on the Clarke mechanism [11].

5.2.1. *An allocation based on Clarke mechanism*

The use of the Clarke mechanism [1,11] is motivated by the following desirable properties: dominant strategy incentive compatibility, allocative efficiency, and individual rationality. The Clarke mechanism works by first choosing an optimal outcome based on the reported cost curves of the bidders and then determines the monetary transfers through the Clarke payment rule. Essentially, to determine the the monetary transfer to division i, the Clarke payment rule drops player i from the mechanism and solves the new problem to obtain a cost minimizing allocation without i. The player i's payment is exactly the total amount by which the other agents are worse off due to agent i's presence. In the above example, the Clarke payments by the company to the division 1, division 2, division 3 and division 4 can be computed to be the following: 1600 to division 1; 800 to division 2; 800 to division 3; and 0 to division 4. The Clarke mechanism also satisfies the weak budget balance property. It is to be noted however that, even though the Clarke mechanism is AE, DSIC, IR, and WBB, the company ends up paying large amounts to its divisions. This is a well known drawback of the class of VCG mechanisms. One way in which this could be avoided is by relaxing the requirement of incentive compatibility from DSIC to the much weaker BIC. This suggests the dAGVA mechanism.

5.2.2. *An allocation based on dAGVA mechanism*

The dAGVA mechanism is due to d'Aspremont, Gerard-Varet, and Arrow [1] and achieves the properties of Bayesian incentive compatibility, allocative efficiency, and strict budget balance. This mechanism is known to significantly reduce the payments, which reduces the cost to the company. A major disadvantage of this mechanism is that it is not individually rational. That is, by participating in the mechanism, a division may actually end up with a negative utility. This would be a severe deterrent on the participation of divisions in a company-wide carbon reduction program.

5.2.3. *An allocation based on optimal mechanisms*

An optimal mechanism in the context of carbon reduction is one which minimizes the total cost of carbon reduction subject to Bayesian incentive compatibility and individual rationality conditions being satisfied. The classical Myerson auction [22,1] is a pioneering example of an optimal auction when there is only one indivisible item. Gautam, Hemachandra, Narahari, Prakash, Kulkarni, and Tew [45] have extended the classical Myerson auction to the setting of a procurement auction for multiple units of a single homogeneous item with volume discount bids. Their approach can be used to derive an optimal auction for the current problem of allocation of carbon credit reductions.

5.2.4. *An allocation based on efficient auctions*

An optimal auction such as above may not be allocatively efficient. Krishna and Perry [46] have proposed an auction that minimizes the cost subject to dominant strategy incentive compatibility, allocative efficiency, and individual rationality. Such an auction is called an efficient auction. It would be interesting to develop a similar mechanism in the current context of the carbon reduction allocation problem.

5.2.5. *An allocation based on redistribution mechanisms*

The use of a Clarke mechanism based allocation has the advantage that the mechanism satisfies properties such as DSIC, AE, IR, and WBB. However, it is observed that the payments to be made by the company to the divisions can be quite high if the Clarke mechanism is used. Since the divisions are all a part of the overall company, one can question if there is really a need to make payments to the divisions. Is there a way we can make the divisions return the money to the company without compromising on the AE and DSIC properties? The answer lies in using the class of mechanisms proposed called redistribution mechanisms [47]. The idea of a redistribution mechanism is to reduce the monetary transfers as far as possible without violating the AE and DSIC properties. Most of the redistribution mechanisms have been developed for forward auctions and it would be interesting to explore such redistribution mechanisms to reverse auction settings such as the carbon reduction allocation problem.

5.2.6. *Combinatorial allocation mechanisms*

Combinatorial auctions are those where there are multiple types of items and the bids are on combinations of items. See the paper by Narahari and Dayama [48] for a review. If the carbon reductions are required for different types of carbon credits (such as discussed in Section 2.3.2), then combinatorial allocation mechanisms become relevant. The use of combinatorial bids in the carbon reduction allocation setting makes the allocation problem complex and leads to interesting, challenging problems in mechanism design and algorithm design.

6. Conclusions and future work

Increasing awareness about climate change and global warming and the intensive world-wide efforts for addressing climate change issues have spurred countries and global industries to initiate strong programs in the area of carbon economics. Carbon credits have become highly valuable and strategic instruments of finance in the global market and it is critical for leading industries to have a well thought out strategy for carbon credit trading to maximize the global good of the industry. This paper has attempted to make a convincing case for using mechanism design to model and solve typical carbon economics problems faced by global industries.

We have described only one problem in some detail (carbon credit allocation problem). Other immediate problems that are waiting to be formulated and solved are the carbon credit selling, carbon credit buying, and the carbon credit exchange problems. These are problems at the level of an industry.

There are many problems at higher level of abstraction, namely at the country level and the world level. We believe game theory and mechanism design offer an extremely promising mathematical framework for addressing carbon economics problems at various levels of abstraction. We mention below few such problems:

- Future contract design and signing will be an important area as most of the trade in EU and India is done using bilateral futures contract.

- As frequent audits will be required to determine carbon footprints, the verification and validation of carbon credits for organizations will be a big business.
- OTC (over the counter) trade of carbon credits is low since it involves risks for parties - Intelligent solutions that mitigates risks will bring in higher trade.
- Design of Banking and Borrowing mechanism for carbon credits.
- Design of Insurance mechanisms for carbon credits generated to protect and instill confidence in investors.

We strongly believe that game theory and mechanism design have a great deal to offer in modeling and solving these problems.

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7. Glossary

Allocative efficiency

An auction is said to be allocatively efficient if it maximizes the total value of allocation. This implies that the objects are allocated to the agents who value them most.

Annex I Countries

Annex I countries include industrialized countries and economies in transition. There are 40 Annex I countries. These industrialized countries are committed to reduce their greenhouse-gas emissions to 1990 levels by the year 2000. They have also accepted emissions targets for the period 2008-12 under Kyoto protocol.

Annex II Countries

Annex II countries include developed countries which pay for costs of developing countries. There are 23 Annex II countries. European Union is a member of Annex I and Annex II countries.

Auction

An auction is a mechanism to allocate a set of goods to a set of bidders on the basis of *bids* submitted by prospective buyers and *asks* offered by prospective sellers. The *willingness to pay* of a buying agent is the maximum amount the agent is prepared to pay for the goods being auctioned while the *willingness to sell* of a selling agent is the minimum price at which the agent is prepared to sell the goods. Typically, in an auction, the willingness to buy and the willingness to sell (also called valuation of the object) would be private information of the respective agents. An auction could be a forward auction, reverse auction, or double auction.

Best response strategy

Given a player i and a strategy profile of the rest of the players s_{-i}, a strategy s_i is said to be a best response strategy against s_{-i} if s_i maximizes the payoff among all possible strategies for player i, when the rest of the players play s_{-i}.

Carbon Credit

Carbon Credit is an allowed emission equivalent to one metric tonne of CO_2 emissions.

Carbon Credit Allocation (CCA)

A mechanism to allocate the carbon credits among the carbon emitting agents by a carbon allocating authority on whom a cap on carbon emission is imposed by a carbon regulating authority.

Carbon Credit Buying (CCB)

A mechanism to procure the required number of carbon credits from a competitive market consisting of multiple sellers.

Carbon Credit Selling (CCS)

A mechanism to sell extra carbon credits in a competitive market consisting of multiple buyers.

Carbon Credit Exchange (CCE)

Carbon Credit Exchange is a mechanism whereby different countries/states/companies/individuals buy/sell carbon credits.

Carbon dioxide (CO_2)

A naturally occurring gas. It is also a by-product of burning fossil fuels and biomass, other industrial processes and land-use changes. It is the main greenhouse gas that affects anthropogenic changes to the earth's temperature.

Carbon footprint

Carbon footprint is a measure of the impact of our activities on the environment, and in particular on climate change. It relates to the amount of greenhouse gases we are producing in our day-to-day lives.

Carbon market

A popular trading system through which countries may buy or sell units of greenhouse-gas emissions in an effort to meet their national limits on emissions under some agreement. The term comes from the fact that carbon dioxide is the predominant greenhouse gas and other gases are measured in units called "carbon-dioxide equivalents."

Certified Emission Reductions (CER)

Certified Emission Reductions (CERs) are issued for emission reductions from Clean Development Mechanism (CDM) project activities.

Chicago Climate Exchange

It is North America's only voluntary, legally binding greenhouse gas (GHG) reduction and trading system for emission sources and offset projects in North America and Brazil.

Clean Development Mechanism (CDM)

A mechanism under the Kyoto Protocol through which developed countries may finance greenhouse-gas emission reduction or removal projects in developing countries, and receive credits for doing so which they may apply towards meeting mandatory limits on their own emissions.

Climate change

As defined by the United Nations Framework Convention on Climate Change (UNFCCC), a change in climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability over comparable time periods.

Common knowledge

Aumann (1976) defined *common knowledge* as follows: A fact is common knowledge among the players if every player knows it, every player knows that every player knows it, every player knows that every player knows that every player knows it, and so on.

Compliance

Fulfillment by countries/businesses/individuals of emission and reporting commitments under the UNFCCC and the Kyoto Protocol.

Copenhagen summit

The conference in Copenhagen is the 15th conference of parties (COP15) in the Framework Convention on Climate Change. The COP15 Copenhagen Conference took place between December 7th and December 19th 2009, and officials and ministers from 192 countries attended the conference. The central aim of the Copenhagen Climate Council is to create global awareness to the urgency of reaching a global agreement on how to tackle climate change at the UN Climate Conference in Copenhagen, December 2009. However, the results fell far short of what Britain and many poor countries were seeking and thus leaving months of tough negotiations to come in the future.

Dominant strategy equilibrium

A strategy s_i^* is said to be a dominant strategy if it is a best response action for player i against any profile of strategies of the rest of the players. A vector of dominant strategies $(s_1^*, s_2^*, \ldots, s_n^*)$ is called a dominant strategy equilibrium.

Double auction

A double auction involves multiple selling agents and multiple buying agents who specify their asks and bids, based on which they trade objects. A double auction is an appropriate mechanism for a multiple buyer, multiple seller market (also called an exchange).

Emission

Release of greenhouse gases into the atmosphere.

Emission permit

The right to release a specified quantity of greenhouse gas under Emissions trading scheme.

Emission price

The cost of releasing greenhouse gases into the atmosphere. Often referred to as the carbon price.

Emissions trading

One of the three Kyoto mechanisms, by which an Annex I Party may transfer carbon credits to or acquire credits from another Annex I Party. An Annex I Party must meet specific eligibility requirements to participate in emissions trading.

European Climate Exchange

The European Climate Exchange (ECX) was launched by Chicago Climate Exchange (CCX) in

2005, and is now the leading exchange operating in the European Union Emissions Trading Scheme.

European Energy Exchange

European Energy Exchange (EEX), Germany's energy exchange, is the leading energy exchange in Central Europe.

Game theory

Game theory may be defined as the study of mathematical models of *conflict* and *cooperation* between rational, intelligent decision makers. Game theory provides general mathematical techniques for analyzing situations in which two or more individuals (called players or agents) make decisions that influence one another's welfare. More appropriate phrases to describe game theory are *Conflict Analysis* and *Interactive Decision Theory*.

Greenhouse Gases (GHGs)

The atmospheric gases responsible for causing global warming and climate change. The major GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20). Less prevalent –but very powerful – greenhouse gases are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

Forward auction

A forward auction is one where there is a seller (auctioneer) who wishes to sell one or more objects to a group of interested buying agents. A forward auction is an appropriate mechanism for a single seller, multiple buyer market.

Global warming

An increase in the average temperature of the earth's atmosphere, especially a sustained increase sufficient to cause climatic change.

Incentive compatibility

An auction is said to be incentive compatible (IC) if all the bidders find it a best response to report their true private information. IC is of two types: DSIC (dominant strategy IC) and BIC (Bayesian IC). A DSIC auction is one in which each bidder finds it a best response to reveal true private information, no matter what is revealed by the other bidders. A BIC auction is one in which each bidder finds it a best response to reveal true private information whenever all other bidders also reveal their true private information.

Individually rational

A mechanism is said to be individually rational iff the agents are not worse off by participating in the mechanism than by not participating.

Intelligence

A player is said to be intelligent if the player knows everything about the game that a game theorist knows and the player can make any inferences about the game that a game theorist can make. In particular, an intelligent player is *strategic*, that is, fully takes into account his knowledge or expectation of behavior of other players in figuring out what the best response strategy should be.

Intergovernmental Panel on Climate Change (IPCC)

Established in 1988 by the World Meteorological Organization and the UN Environment Programme, the IPCC surveys world-wide scientific and technical literature and publishes assessment reports that are widely recognized as the most credible existing sources of information on climate change.

Joint Implementation (JI)

A mechanism under the Kyoto Protocol through which a developed country can receive "emissions reduction units" when it helps to finance projects that reduce net greenhouse-gas emissions in another developed country (mostly the recipient country is an "economy in transition").

Kyoto Protocol

Kyoto Protocol is an international agreement standing on its own, and requiring separate ratification by governments, but linked to the UNFCCC. The Kyoto Protocol, among other things, sets binding targets for the reduction of greenhouse-gas emissions by industrialized countries.

Kyoto mechanisms

Three mechanisms are established under the Kyoto Protocol to increase the flexibility and reduce the costs of making greenhouse-gas emissions cuts: Clean Development Mechanism, Emissions Trading and Joint Implementation.

Marrakesh accords

Marrakesh accords include details for establishing a greenhouse-gas emissions trading system, implements and monitors the Clean Development Mechanism.

Mechanism Design

Mechanism Design is the art of designing rules of a game to achieve a specific outcome in the presence of multiple self-interested agents, each with private information about their preferences. Mechanism design provides a scientific framework for design of auctions. Mechanism design uses the framework of Bayesian games, which are strategic form games with incomplete information.

Mitigation

In the context of climate change, a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Examples include using fossil fuels more efficiently for industrial processes or electricity generation, switching to solar energy or wind power, improving the insulation of buildings, and expanding forests and other "sinks" to remove greater amounts of carbon dioxide from the atmosphere.

Nash equilibrium

A Nash equilibrium is a vector of strategies, one for each player, such that for each player, his/her Nash equilibrium strategy is a best response strategy when all other players choose to play the strategies specified in this Nash equilibrium.

Procurement auction

In a procurement auction, there is a buyer who wishes to source one or more objects from a group of suppliers or sellers, using an appropriate reverse auction model.

Rationality

A decision maker or a player is said to be *rational* if the player makes decisions consistently in pursuit of his own objectives. It is assumed that each player's objective is to maximize the expected value of his own payoff, measured in some utility scale.

Registries, Registry systems

Electronic databases that will track and record all transactions under the Kyoto Protocol's greenhouse-gas emissions trading system (the "carbon market") and under mechanisms such as the Clean Development Mechanism.

Reverse auction

A reverse auction is one where there is a buyer (auctioneer) who wishes to buy one or more objects from a group of prospective selling agents. A reverse auction is an appropriate mechanism for a single buyer, multiple seller market.

Rio conventions

Three environmental conventions, two of which were adopted at the 1992 "Earth Summit" in Rio de Janeiro: the United Nations Framework Convention on Climate Change (UNFCCC), and the Convention on Biodiversity (CBD), while the third, the United Nations Convention to Combat Desertification (UNCCD), was adopted in 1994. The issues addressed by the three treaties are related – in particular, climate change can have adverse effects on desertification and biodiversity.

Strategic form game

A strategic form game consists of a set of players, $N = \{1, 2, \ldots, n\}$. Each player has a set of strategies or actions from which to choose his strategy. Each player is associated with a utility function that assigns to every profile of strategies of the players a utility value. Each player chooses a strategy to play simultaneously independently of one another.

United Nations Framework Convention on Climate Change (UNFCCC)

An international treaty adopted after the Rio Earth Summit in 1992 and aimed at achieving the stabilization of greenhouse gas concentrations in the atmosphere.

VCG mechanisms

Vickrey–Clarke–Groves mechanisms constitute an important special class of mechanisms that enjoy the desirable properties of allocative efficiency and dominant strategy incentive compatibility. Vickrey mechanisms (proposed in 1961) are a special case of Clarke mechanisms (proposed in 1971) while the Clarke mechanisms are a special class of Groves mechanisms (proposed in 1973).

Winner determination

The winner determination problem determines who among the bidders will be allocated the objects in an auction based on certain well defined objectives.

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