**THE ALBERTA CARBON MARKET: AN EXPLORATION OF ALTERNATIVE POLICY OPTIONS THROUGH AGENT-BASED MODELING**


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## Dedication

To:

The arms that taught me to war

The hearts that taught me to love

The minds that taught me to dream

- and the lips that taught me to keep moving

To DMBMB

**Abstract**

Our study examines some design alternatives for a carbon market by exploring the fledgling Alberta carbon market. We attempt to evaluate the performance of these designs on the bases of trade volume, cost efficiency and stability. To achieve this we construct an empirically-calibrated but simple agent-based model, certain aspects of which we selectively modify to incorporate various design options. We make comparisons among these options based on data simulated from the ensuing family of models.

We find strong evidence that in general, market design features such as source-of-credits, the scale of the market, and pricing-mechanism are very important considerations that influence the performance of the market. In addition, we find support for the notion that the level of the price cap relative to the average cost of abatement in the market matters, and beyond a threshold, higher price caps are associated with lower levels of performance.

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**Chapter 1: Introduction**

Over the past decade and half, putting a price on carbon emissions has emerged as the single most promising component of any combination of strategies for mitigating climate change. Its rationale is straightforward: if there is a reasonable cost attached to polluting, then there is an incentive to avoid emitting more than is necessary and sustainable. However, what price to put on carbon emissions (in essence, what this 'reasonable cost' should be) and how to arrive at this price such that it is effective enough to align production and consumption patterns with environmental goals remain much debated issues. While some policy-makers and researchers such as Stiglitz (2010) and Mankiw (2009) favor a carbon tax mostly for its simplicity and direct effect on price; others support mitigation through a cap-and-trade framework due to its advantages with respect to the certainty it affords in meeting emissions-reduction targets, its efficiency in cost allocation (as observed by Yang & Oppenheimer, 2007) and tolerability in a tax-averse world; while others yet (for example Hepburn, 2006) advocate a combination of these two tools.

In combination with other policies, market-based cap-and-trade systems have been successfully used before (for instance to reduce Sulphur-Dioxide emissions (NAPAP Report, 2005)), and so have become appealing to policy-makers as a dominant and electorate-favored tool which could effectively mitigate global warming, and efficiently allocate costs while encouraging sustainable growth and development. By internalizing the environmental cost of business–a negative externality–into corporations' cost functions for example, cap and trade programs have the potency of birthing a cost structure that makes firms responsible for the effect of their activities on the environment, without necessarily stifling economic growth.

This thesis explores design issues and dynamics in the Alberta cap-and-trade system within a Complex Adaptive System (CAS) framework. We choose to examine the Alberta carbon market for three major reasons. First, according to Environment Canada (2012), Alberta– home to about 10% of Canadian population– emits a huge percentage (about 33%) of the total national

inventory of carbon-dioxide, and is expected to witness massive growth in emissions due to its expanding oil exploration and power consumption. This makes it an interesting market to study, and a very important one to understand given its significant role in meeting (or not meeting) Canada's carbon-reduction targets. Secondly, it is a closed system at present within which only Alberta-raised credits can be traded or tendered; this presents us with the rare facility of a detached compliance market devoid of complicated and little-understood linkages to other carbon markets such as the EU and UK Emissions Trading Schemes. Thirdly and necessarily, we require a market for which some qualitative and quantitative data, such as trends, forecasts, and policy-papers, are readily accessible to enable close calibration of our model; the Alberta market satisfies this prerequisite.

We also choose to examine this market through an agent-based CAS approach for four reasons. Firstly, as explained by Bonabeau (2002), agent-based modeling captures emergent phenomena and is useful for modeling markets where interacting agents are heterogeneous and network effects may result. The Alberta Carbon Market is composed of at least six major classes of corporations, varying from very large electricity-generating coal-power plants and oil-sands facilities to much smaller chemical, fertilizer, cement and lime processing plants (Environment Canada, 2012). Some of these companies are mining companies, others are manufacturing companies, while yet others are service companies which for instance have significantly different cost structures. It is therefore necessary to represent these agents at a microscopic level in order to capture their heterogeneity in terms of size and behavior, and closely model interactions which may occur among them. This holds the promise of enhanced realism and its gains in our developed models.

Secondly, since our exploration is of an actual market currently populated with one hundred participants which show features of an oligopoly (Goddard, Haugen-Kozyra, & Ridge, 2008), and as Kurz-Milche and Gigerenzer (2007) among others report, in the absence of perfect information (a defining feature of imperfect markets), agents in the real world are likelier to make

some decisions by "if-then" (conditional) rules and threshold conditions rather than by optimizing sets of differential equations, our study shall benefit from a framework within which such rules can be defined and allowed to interact.

The third reason is the flexibility afforded by agent based modeling which allows such realistic features as memory and adaptation to be incorporated into models at a microscopic level. This advantage from using agent-based modeling software also enhances the level of realism in the models we use since actors in actual markets show evidence of both features. Our fourth reason still borders on flexibility, but in the different sense that agent-based modeling naturally allows us to tune the level of description or aggregation of agent behaviour as appropriate. This feature proves indispensable since our modeling shall involve some tinkering to determine the most useful levels of behavioral aggregation.

In chapter two we provide some general background by discussing some relevant issues concerning carbon markets; contrast various emission cap-and-trade schemes at regional, national and provincial levels; discuss the relative contributions and failures of international policies and conventions; and further describe the Alberta carbon market, highlighting details that shall be emphasized in our subsequent modeling. In chapter three we discuss research questions, while chapter four reviews extant Agent-Based Modeling literature, describes details pertinent to model design, and clarifies some of the technical considerations informing the models that we develop. Chapters five and six describe experiments designed to explore our research questions and present the simulation results respectively, and we conclude the study by discussing its limitations and proffering recommendations in chapter seven.

Given the novelty of the carbon market, it is currently unclear as to what precise structure and policies will lead to a healthy market. This study is therefore aimed at achieving two broad goals; firstly, specifying simple agent based models of the carbon market and simulating activity on them, and secondly analyzing the data generated from the simulations with a view to gaining

an insight into the dynamics of the market so defined in the hope of uncovering some of the

effects of alternative structures, strategies and policies on carbon-pricing and emissions reduction.

## Chapter 2: Literature Review

### 2.1    Background

In this preamble, we give a brief discussion of the general problem of emissions within the context of climate change. In the first and second subsections we review the major arguments of alternative views in climate-sustainability debates respectively. The aim is not to resolve these issues in this paper, but to present a general sense of contemporary debates which constitute the broader context within which our research is situated. Next, we give a description of major carbon markets around the world and subsequently progress into the Canadian scenario. We cap the discussion with a detailed description of the Alberta Carbon market.

We define the emissions problem as equivalent to the problem of anthropogenic global warming.[1] Global warming is a phenomenon that constitutes an increase in average temperature over the earth due to an excess of Greenhouse gases such as carbon-dioxide, methane, nitrogen-oxide, ozone and water-vapor in the atmosphere, which in recent times has been chiefly caused by mans' incessant burning of fossil fuels (Houghton et al., 1996; Karl & Trenberth, 2003). Anthropogenic global warming (hereafter simply referred to as 'global warming') is a looming threat to our world today- a scary threat that our consumption and production habits over past years have caused excessive pollution and could doom the earth and make it uninhabitable in a few centuries to come. Sea levels are rising and are expected to rise even further, weather patterns are spiralling dramatically outside the norm, frequent extreme weather occurrences have and will likely continue to ensue, agricultural yield will necessarily drop, and some organisms in this ecosystem (including humans) are likely to be unable to adapt rapidly enough and go extinct. These are just a few of the consequences of unbridled global warming trends identified by Houghton (1994) and supported by several others (see Elsner, Kossin, & Jagger, 2008; WMO

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[1] We recognise that broadly defined, the emissions problem includes immediate health hazards from air pollution as well as the undesirability of living near an emitting source. We narrowly define the emissions problem within the context of global warming here because of its currency, heavy consequences, global nature, and time-sensitivity. Our definition therefore only adheres with the theme of the ongoing global emissions discourse.

Report, 2011). If our production and consumption processes remain ingrained with practices that heavily emit greenhouse gases, it is unlikely that they could be sustained for long. Worse still, by continuing on the current path, the world as we know it today may self-destruct.

Beyond climate expert opinions, we may indeed have started to experience the effects of global warming first-hand if we consider the recent spate and magnitude of natural disasters that can be explained by global warming. The Year-2002 floods in Saxony (Germany), European heat waves of 2003, Year 2005 US Hurricane-Katrina, Year-2010 Pakistani Floods and Russian wildfires, Year-2011 Canadian wildfires, Australian cyclones and floods, Japanese Tsunamis and earthquakes, and US record-breaking tornadoes, are a few of the disasters that more recently occurred and had grave consequences for both life and property (Barthel & Neumayer, 2012). Some evidence has been found also linking these disasters to global warming. Rahmstorf and Coumou (2011) for instance, report an 80% probability that the 2010 Russian and Australian wildfires were caused by global warming. Also, Bender et al. (2010) find a strong link between global warming and the frequency of intense hurricanes, and predict a doubling in the frequency of tropical cyclones by the end of the 21$^{st}$ Century. It is noteworthy that these events are spread across continents; global-warming effects are generally described by experts such as Barrett and Stavins (2003), as global and not localized, despite the fact that they are emitted in and by entities in a specific community, state, or country. This feature underscores the need for a global response with shared responsibilities.

The foregoing also underlines the general need for a change in how we live, in order to preserve the earth. Practices in manufacturing, agriculture, exploration, and transportation especially need to be revised with the aim of reducing their current negative environmental externalities. Since industries thrive on energy, this roughly translates to the development of alternative energy sources which shall reduce our dependence on fossil fuels. The burning of fossil fuels for energy has been identified as the heaviest culprit in greenhouse gas emissions. The majority of the world's heavy emitters are linked with the global energy sector. Fossil-fuel-fired

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electricity-generating plants and oil-prospecting and processing units are particularly notorious and together, account for about 26% of global GHG emissions (IPCC, 2007). Transportation sectors–which rely heavily on energy–also contribute meaningfully to emissions, while de-forestation and agricultural practices such as over-tilling play a large part in countries with large construction or agrarian communities. In 2004, transport sector fossil fuel combustion was responsible for 13%, agriculture and forestry together accounted for 31%, while industry had a share of 19% of GHG emissions (IPCC, 2007). In developed countries such as Canada and US, the major villains are almost always electricity-generating companies, and oil and gas companies. Since all economic sectors run on energy, substituting other methods of energy generation should lead us to a cleaner and healthier world. However, this has proven an inadequate strategy due to limits to the speed of development of technologies that efficiently harness alternative sources.

**2.1.1   Alternative   strategies   for   combating   climate   change.** Energy-source substitution on a global scale cannot be an instantaneous occurrence; therefore three other options are concurrently being pursued by relevant stakeholders.  The major option that is being given the most attention currently is mitigation; which is described by Verbruggen (2007), as entailing the reduction of emissions by the establishment of projects that reduce anthropogenic emissions of greenhouse gases into the atmosphere. These projects include those that enhance and reward the efficient industrial use of fossil fuels, renewable energy projects, and carbon-sink forestry projects (Stern Review, 2007). The main focus of mitigation is on carbon emissions which account for about 75% of global greenhouse gas emissions (IPCC, 2007)[2]. The emission-reducing projects are expected to be paid for ultimately by emitters, who shall be required to buy up chunks of them (called emissions allowances) in order to continue producing after exceeding their allotted emissions limit (Stavins, 2008). The added cost of production from purchase of emissions

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[2] Consequently for the rest of the study we use "carbon emissions" in the loose sense of "greenhouse gas emissions" except in few parts where the discourse is sensitive to their distinction. Also see Appendix A for a pie-chart representation of emissions by gases in 2010.

allowances may itself discourage excessive emissions and encourage firms to develop better emissions-efficient processes and technology- thereby speeding up the process of achieving more sustainable habits in pursuit of an inhabitable future.

The second option is climate geo-engineering. Geo-engineering takes a radically different approach from abatement. In the Royal Society's (2009) report, it is described as a deliberate effort to mediate the effect of excessive greenhouse gases (particularly carbon-dioxide) on our environment by employing large-scale climate-engineering solutions that either seek to remove greenhouse gases from the atmosphere, or to cause the earth to absorb less solar radiation. The report lists some methods of carbon-dioxide removal (CDR) such as carbon sinks, biomass for carbon sequestration, direct engineered capture of $CO_2$ from the atmosphere, and ocean fertilization as well as some methods of solar radiation management (SRM) such as earth-surface albedo enhancement, marine-cloud reflectivity enhancement, sulphate-aerosol injections, and space-deflectors. The major difference between CDR and SRM approaches is that CDR approaches attempt to tackle the problem at its root by removing the excess carbon-dioxide, while SRM methods focus on correcting radiation imbalance by shading or shielding the earth (see Lenton and Vaughan (2009) for a detailed discussion of the two methods). The popular view among climate experts was echoed by Lawrence (2006) in a *Climate Change Journal* editorial and more recently voiced as well by others in the Robert Bosch Stiftung (2012) climate podium discussion in Potsdam; geo-engineering holds some promise for the near-future and should be vigorously researched, for now we know too little about its effectiveness and risks to deploy its tools as a large-scale response to climate change.

A third option–adaptation–is defined by the EU (2011a), as "anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause". This option is a crisis control strategy which cannot be entirely separated from the other two options, but which is distinct to the extent that it aims at boosting resilience to extreme weather conditions such as floods and cyclones, and enhancing efficiency in the management of

scarce natural resources including forests and water, rather than trying to reduce or neutralise the effect of greenhouse gases. Its theme is that climate change might not be entirely preventable, and humanity must be prepared when some extremely damaging changes start to appear. This option is stimulated in large part by the recent wave of natural disasters.

Both mitigation and geo-engineering have their strengths and weaknesses. Mitigation tools tend to be much slower and more expensive, but yield results over a long period, while geo-engineering methods are faster and cheaper to deploy but mostly yield shorter-term benefits and may have severe side-effects on ecosystems among other possible risks. Rather than being viewed as alternatives, it may be more fruitful to consider these as different components of a coherent portfolio of contingent strategies which may each address very distinct but related problems. Mitigation is deemed by many such as Canadell et al. (2007) as ineffectual as a sole policy, and they advocate geo-engineering as a potent supplement required to arrest the climate change situation. Robock (2008) caution against the deployment of certain geo-engineering methods–particularly SRM techniques–and many climate experts like Angel (2006) also hold the reasonable view that this supplement should only be used in emergency situations where very dramatic catastrophe, due to climate change, is imminent.  Further research into geo-engineering seems necessary since the climatic trends appear to be increasingly difficult to predict, and such drastic measures might be necessary as a first response to certain disasters, despite their possible side-effects.

In general, the environmental-sustainability debate on how to tackle global warming, and consequently climate-change, is very active. Research into methods is mostly vibrant since much less appears known than unknown. Actual policies however, that assuage the problem require much less uncertainty in projections of impacts, costs and risks as we now have. As a result, policy-makers appear hesitant, perhaps only reflecting the doubts and confusion of the global polity; or perhaps reflecting the gap between scientific and popular understanding of the

emissions problem due to biased coverage of the discourse by the press (see Boykoff & Boykoff, 2004 for an extensive content analysis on this possibility).

### 2.1.2 Some major sustainability debates and issues.

*2.1.2.1 Emissions reduction versus emissions intensity reduction.* Cap and Trade systems function by imposing a limit (cap) on the quantity of allowable emissions in a system, which causes a scarcity of emission-allowances and thus creates a market phenomenon. That limit could either be an absolute one, or a relative one. An absolute limit specifies an amount of greenhouse gas emissions that must not be exceeded within a period of time while an intensity-limit specifies the amount per unit of production. Obviously, intensity limits emphasize efficiency while absolute limits emphasize specific targeted quantities. Invariably, both limits aim at achieving behavioral changes with respect to emissions; the major difference being in the level of certainty about the magnitude of emissions-reduction that would result, and their implications for economic growth.

Absolute limits have been used before in curbing emissions of Sulphur-dioxide and Nitrous-oxides in the US, and the Kyoto Protocol specifies limits in an absolute sense. However, according to Ellerman and Wing (2003), they are much less commonly used than intensity limits which are used for the US's State Implementation Plans, the EU's Large Combustion Plant Directives, Canada's Carbon Policy, and carbon mitigation plans of many developing countries such as Argentina and India to mention a few.

The main debate currently resides on the efficacy of either limit in reducing carbon emissions. The chief arguments in favor of an absolute cap are that it assures certainty in quantity of emissions to be reduced (thus is useful for precluding emission growth), and is simple to communicate to stakeholders. Its disadvantages are mainly that it could lead to escalating costs, and consequently stifle growth pending the development and accessibility of new carbon-free

technology in the not-so-near future (Nordhaus, 1994). Absolute caps are also criticised for causing and/or perpetuating economic disparities particularly to the disadvantage of less-developed countries, for which economic growth is more tightly coupled with emissions growth and which are unequipped with resources including technology, with which to meet most reasonable absolute targets (Pizer, 2005). Intensity limits on the other hand, have the distinct advantage that they accommodate economic growth and instead focus on performance as a function of efficiency. The key obvious disadvantage of intensity limits is that given accelerating economic growth, emissions may burgeon faster than ever even in the face of decreasing emissions intensity; this will happen insofar as the economy grows faster than emissions.

From the brief expose above, it is rather obvious that the debate is charged, not by intrinsic qualities of either approach, but by how the climate change problem is conceived by different parties. At an extreme, an intensity approach is naturally acceptable to those who believe that the amount of "global-cooling" we can achieve in the short-run through mitigation is not worth the possible sacrifice in economic growth, while, at another, an absolute cap is likely to be more acceptable to those like Hansen et al. (2006), who believe that it is necessary to aggressively tackle global warming before it reaches thresholds that force an irreversible climate change that may potentially result in several degrees of disasters including the melting of permafrost, the extreme consequence of which is the extinction of species including the human race.

While the motivating scenario of the latter viewpoint is indeed possible, it is shrouded in uncertainty. Given this uncertainty, the majority of policy makers the world over seem to have chosen (possibly under the influence of the press) to pursue economic growth on the chance that climate change will not be too harsh. The evidence for this decision seems to be strongly reflected in the prevalence of intensity limits relative to absolute ones. Thus, although absolute caps may be the more effective method (at least from an emission-reduction perspective), as Quirion (2005) opines, intensity limits are more politically acceptable and likelier to thrive subsequently in future emission policies.

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That said, according to a report published by the World Resources Institute (Herzog, Baumert, & Pershing, 2006), how effective either policy-option actually is in reducing emissions depends more on how stringent its application is, how widely defined its scope is, and how legally binding its compliance is. Even an intensity limit could be made very stringent, defined to capture most significant sources and be made mandatory by law enough to yield substantial mitigation dividends, whereas an absolute cap may be made so high, encompass few significant sources, and left open to volition such that it hardly has any impact. Such a high absolute cap is however likely to be more easily perceived as weak than an equally ineffective intensity target which often deceptively appears high and ambitious. This was well demonstrated by the Bush administrations 2001 intensity-based policy follow-up to its withdrawal from Kyoto (see Kolstad, 2005 for an elaborate discussion).

*2.1.2.2 Emissions taxes versus emissions trading.* Emissions trading and emissions taxing are two alternative market-based approaches to attributing the cost of pollution to emitters[3]. As with most other economic debates, it is unlikely that there is a strictly superior policy option between emissions taxes and emissions trading. In a world of absolute certainty, both options should yield equivalent results (Green, 2008). However, we live in a world fraught with uncertainty and either option is only more likely to be effective in certain circumstances, while being less effective in others. In order to appreciate this point, we briefly explain the theoretical mechanisms of both market-based instruments, and conclude with comments on instances where each could be an effective policy option.

The theoretical underpinning of emissions taxes, as observed by Elkins and Barker (2002), is generally agreed on by economists; if the production of a commodity causes negative externalities not reflected in the price of that commodity, social welfare can be improved by

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[3] A third approach–regulation–is generally unpopular among policy-makers due to its inherently high cost, potential damage to industry and economic growth, and poor efficiency relative to market mechanisms (taxes and trading schemes).

imposing a tax. This is particularly true if revenue from the tax collected is used in tackling the externalities or the problems caused by them. Emissions taxes are designed to tackle the emissions problem by fixing a price per unit of emission, and allowing those on whom the burden is imposed to determine how much to emit. However, an emissions tax has to reflect the social cost of the taxed good to a reasonable degree in order to increase the price of emission-intensive production, thereby making emission-intensive products less competitive relative to low-emission substitutes. Thus, it aims at achieving behavioral change using a direct price-fixing mechanism that reflects the popular "polluter pays" principle. Each participant in the system it covers is levied an amount of tax per unit of emission released in the course of its production or consumption process. In theory, emission-taxes equalise marginal abatement costs across all emitters and can achieve emission reduction at the least cost to society. By and large emission-taxes are simple and easy to communicate to stakeholders. While electorates and industry are usually tax-averse, a carefully designed emission-tax, revenues from which might be used to grant the low-income class some meaningful rebates from other historically unpopular taxes or fund some welfare program, is likely to meet with acceptance. One primary problem that faces the international adoption of the carbon tax strategy is the fact that it is virtually unrealistic for countries that hitherto protected, supported, and even subsidized their energy sector and other heavy emitters, to suddenly erase those policies and start to penalize these same industries upon which their growth has been predicated. Another issue with a tax is that it has to be applied with considerations for the point at which its ultimate burden falls. This means that to tax the energy sector of a country for instance, electricity consumption will be taxed while oil and gas will have to be taxed at the extraction and processing stages because the bulk of those products are consumed externally. The implication is that a single tax policy will not suffice–each sector to be taxed has to be examined carefully.

On the other hand, emissions trading is designed to fix the quantity of emissions allowed within an economic system at the level of a predetermined target, and by the scarcity that ensues,

create a market within which price is formed. Players within the trading system are then left to determine the least costly way to meet the effective limit by buying or selling emission permits (Sijm, 2005). The expectation is similar to that of a tax; polluting firms get punished by incurring the added cost of buying emission-permits, and attempt to explore low-carbon technologies and processes in order to avoid that cost. Those who switch successfully and are able to reduce their emissions below a given benchmark–for example 21% below 1990 emission benchmark levels in the EU ETS Phase III plan (UK Department of Climate Change, 2008)– generate permits that they can resell to those who still require them for compliance purposes. Herein lies the main appeal of emissions trading systems; under them, emitters have an incentive, not only to reduce their pollution in order to avoid compliance costs but, to reduce emissions beyond the statutory requirement through innovation, and thereby generate permits which they can sell. This spells competitive advantage for such proactive participants, and a least-cost reduction in emissions to society, by creating a compliance system in which those emitters who find it most economical to reduce their emissions do, while others without that comparative advantage can simply purchase from them.

Emissions' trading however is not without some serious demerits, some of which are high price-volatility and high susceptibility to corruption. Nordhaus (2005) reviews several emissions markets within which volatility is rife, while data from the European energy exchange (2005, 2006,) indicate that EU allowance prices fluctuated by more than 15% monthly on average between May 2005 and April 2006, and experienced an 80% crash and equivalent recovery in the subsequent 3 months. Similarly, the US Environmental Protection Agency (2012) reports annual average fluctuations in Sulphur-dioxide permit prices of over 40% between 1997 and 2012, with price increasing from $106 in 1997 to $860 in 2006 and $2 in 2011. Such volatility if experienced on a global scale portends huge costs and shall negatively impact both the business and consumption of carbon-intensive economies, potentially crippling them. Taxes on the other hand

are by design not sensitive to the changes in weather or economic growth that drive volatility. Subsequently in this study, we examine the effect of alternative market designs on volatility.

Trading also leaves more room for cheating than taxes would for the mere fact that among other reasons, governments are naturally more incentivised to perform their monitoring and enforcement roles under tax regimes where they collect revenue, than in a trade scenario (Nordhaus, 2005). Moreover, taxes could be easily administered through pre-existing tax collection mechanisms while emissions trading would require the design from scratch of new mechanisms.

Weitzman (1974), and subsequently Hepburn (2006), attributed the objective determining factor in choosing between both options to the region of uncertainties. Weitzman showed in his much-acclaimed paper "Prices vs. Quantities" that where there is uncertainty about the cost functions or a possibility that costs are very sensitive to above-optimal emissions reduction, a tax is preferable; whereas where the uncertainty lies in the damage function (that is how grave the impact of that externality is) or where the damage function may be very sensitive to above-optimal level of emission, a trading system is preferable. Cost function uncertainties are already being resolved, and are likely to be mostly resolved in the near future, however damage function uncertainties are unlikely to vanish even in the long run. Therefore, given this criterion, our current climate predicament seems to support some combination of both instruments in the short run (after which cost functions will likely become more certain), while trading will be preferred as a longer term instrument.

In essence, the more appropriate question for debate may not be "Which is better?", but "How much of each to use and when?" This raises further hard questions of how such policy-instruments could best be combined to avoid conflicts such as distortion of substitution objectives (Sorrell & Sijm, 2003), instrument-redundancy and other practical problems that breed inequity. In any case whatever instrument choice is made, adequate commitment must be made to its enforcement, stringency and coverage in order to reap any significant benefits.

In administering carbon taxes in the short-run, it is also practically useful to remember Baumol and Oates' (1971) work on environmental externalities, which cautions that in the absence of comprehensive information about cost functions, taxes on goods with associated negative external effects, should be applied iteratively in order to meet up with emission-reduction goals, since there is no hard and fast way to know a priori what level of taxes would result in the desired changes. Taxes and trading schemes would both require keen monitoring and continuous adjustments in order to achieve meaningful goals.

### 2.1.2.3 *Are we really serious about mitigation?–Evidence from Montreal to Cancun.*

The previous two sections implicitly raise a profound question; are we really serious about mitigating global warming? We explore this question by examining major international efforts towards arresting climate change to date and weighing them against the requirements indicated by scientific research. We conclude with our value-laden summation of efforts vis-à-vis necessity, and observe some implications for the future.

First, a quick clarification on the "global warming" and "climate change" terminologies; Global warming is generally used to describe the sustained rise in the earth's atmospheric temperature within the past two centuries, while climate change refers to a sustained change in average weather over a protracted period of time or a change in the frequency and magnitude of extreme weather events. In essence, while global warming is predominantly a thermal phenomenon, climate change describes the effects of global warming on the earth, beyond, but including, significantly higher temperatures. Examples of such effects as have been discussed before and mentioned by the renowned environmentalist Bill McKibben (2011) on Aljazeera include; melting of ice glaciers, increased sea levels, mega floods, and increasing thunderstorms. The focus when both terms are used is their impact, whether direct or indirect, short-term or long-term, on mankind. Given that these two are so closely intertwined in meaning, and mentioning

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one presupposes the presence of the other, they are often used interchangeably in climate-relevant discourse. We follow this convention in our study.

According to the United Nations website (http://www.un.org/Depts/dhl/resguide/specenv.htm), in 1968 the UN recommended that the General Assembly convene a conference fielding discussions about "problems of the human environment". Thus the first incursion of climate change into formal international discourse occurred at the 1972 United Nations Conference on the Human Environment (UNCHE), held in Stockholm. It gave the issue international exposure, established the United Nations Environmental Programme (UNEP), and along with several other subsequent forums yielded the "Montreal Protocol on Substances that Deplete the Ozone Layer", which was adopted in 1987 in Montreal, and has since been amended to include agreements reached at the subsequent 1990, 1992, 1995, 1997, and 1999 conventions (UNEP, 2000). The Protocol specified items to be controlled (mostly Chlorofluorocarbons, abbreviated as CFCs) and imposed quantitative limits on national production and consumption of these controlled substances within a regulatory framework. Each subsequent amendment since 1990 has progressively increased the target up to the current point where the production of these compounds is virtually proscribed (UNEP, 2006). The protocol is generally viewed as a huge success to date.

Largely inspired by the Montreal Protocol of the previous year, the first international conference on climate change was held in 1988, and hosted by Canada in Toronto. It prescribed a global emission abatement of 20% (World Meteorological Organization, 1989), and was crystalized by the Noordwijk ministerial conference of 1989 which in its declaration contained prescriptions for tackling emissions (particularly $CO_2$), marshalling the requisite funding, and monitoring emissions. It also encouraged the Intergovernmental Panel on Climate Change (IPCC) to further research emissions targets and reforestation as an abatement strategy, and recommended urgent stabilization of emissions by industrialized nations (UNFCCC, 2012a).

Conventions and meetings for the next 6 years added very minor enhancements due to an impasse occasioned by a fundamental disagreement between the US, Eastern Europe, and Japan on one side and Western European countries on the other. As observed by Bodanski (2011)– whose work we generously draw from in this section–while Western Europe championed the establishment of targets and deadlines, the US-led party antagonized the inclusion of both features in any agreement. Ultimately as a compromise, the Noordwijk Declaration included a rather mild and agreeable stabilization target and merely noted (as opposed to a recommendation) the consensus among developed countries that the deadline should be achieved by the year 2000 (Bodanski, 2011). The US in particular, supported–and still supports to-date–an international strategy where individual nations designed their own programs and strategies which tangibly solved the problem from a bottom-up approach. Eastern and Western Europe then–and the European Union now–supported a top-down approach with agreed targets and binding timetables. The United Nations Framework Convention on Climate Change in 1992 attempted to marry these two ideological perspectives (UNFCCC, 1992), by making a binding requirement that nations develop national programs, while the targets and timelines set within its provisions were non-binding (Bodanski, 1993). Since then, international climate change politics has been defined by tension and a struggle between these two ideologies. While the declaration was good in jumpstarting global environmental awareness and action, it lacked the strength in itself to aggressively tackle the problem of climate change.

A breakthrough, in the form of the Kyoto Protocol, appeared in 1995 when the European clamour for quantitative emissions targets for developed countries were tabled for discussion at the first UNFCCC Conference of the Parties (UNFCCC, 1998). Targets, which were typically a percentage reduction against 1990 emission levels, were agreed on for all developed countries. In 1996, it was agreed among state-negotiators including US representatives that these targets and timetables, which were initially labelled as "objectives", would be legally binding and cover the period 2008 - 2012. Among Kyoto's major strengths was its creation of three mechanisms to

complement national abatement policies towards enhancing flexibility in how countries met their targets. These three market-based tools were: Emissions trading, Clean Development Mechanism (CDM), and Joint Implementation (JI). Their purpose was to stimulate sustainable development through technology transfer and investment, assist committed countries in meeting their targets in a cost-effective manner, and include the private sector and developing countries in the emissions-reduction campaign (UNFCCC, 2012b). JI and CDM were project based mechanisms that enabled developed countries to collaboratively implement emission-reduction projects with other developed countries, and with developing countries respectively. The protocol was adopted by countries in 1997, and took effect from 2005. Kyoto was a giant leap forward in that it inaugurated for the first time a global compliance market which necessitated the outcrop of national and regional compliance markets. It was also quite clear in its terms, and established practical tools for confronting climate change. However, it housed certain flaws from which it suffered major setbacks.

One of four fundamental flaws with Kyoto (at least from a North American perspective) that made it unacceptable to certain parties, was the exclusion of high-emitting developing countries, especially India, Brazil and China (which more recently acknowledged being the world's largest GHG emitter (Buckley, 2010) from emission-reduction commitments by the protocol. According to the then US president George W. Bush, the protocol is unacceptable because "it exempts 80% of the world, including major population centers such as China and India, from compliance, and would cause serious harm to the US economy" (Dessai, 2001, p. 5). The US, which is responsible for about 20% of global emissions (US GOV., 2006)), withdrew from the Protocol in 2001, closely followed by Australia, due to this flaw as well as the US's long-standing ideological preference for a bottom-up approach. In defending the exclusion, China asserts that it is only fair if historical emissions and per capita income were considered; the rich/developed countries have been responsible for the bulk of emissions historically and it is only fair that they take the bulk of responsibility for its reduction, while poorer/ developing

countries are allowed to focus on more pressing national issues of poverty, growth, and development, and participate on a voluntary basis. While China and other developing countries seem justified in campaigning for equity, their emissions currently account for about half of global emissions (Nordhaus, 2005), and given the possible dire consequences of reaching a dangerous threshold in global warming, should be checked in order to arrest the looming threat. Any resolution that makes this possible, while still recognising equity in terms of historical emissions and poverty, has however proven evasive since Kyoto.

Apart from the direct exclusion of developing countries, Shapiro (2007) also explains how the Kyoto protocol effectively excluded Eastern European countries including Russia, by setting a year-1990 baseline for emissions reduction. This explanation summarizes the second major flaw in the Kyoto protocol: Given the final collapse of communism, Russia and the rest of Eastern Europe as well as East Germany shut down most of their inefficient and high-polluting factories just before the year 1990. Thus setting a 1990 baseline for them, masks their historical contribution to climate change, and is tantamount to awarding them negative targets and excess grandfathered permits. Since the US and Japan among a few others witnessed rapid industrial growth post-1990, they would have to purchase those excess permits from Russia and others in order to meet their own targets. Nordhaus (2001), reports from results of his Rice model of climate change that under Kyoto this would have represented annual transfer payments from the US and Japan of about 40billion dollars to Russia and other Eastern European countries. As such, it is not surprising that the US backed out of an agreement under which it would be so penalized, especially given the concurrent relative mildness of German and UK Kyoto targets which allowed them to increase their actual annual emissions while still meeting their targets (Shapiro, 2007). In Nordhaus's (2005) estimate, the immediate consequence of the US's backtracking was the reduction of Kyoto's entire coverage of global emissions from 50% to 30%. Other indirect effects, as we were to see subsequently, were similar exits by Australian and Canadian governments.

The third flaw in Kyoto was its short-term approach reflected in coverage of only five years (from 2008 to 2012) which left post-2012 emissions unregulated. This caused widespread uncertainty about the future of emissions abatement, and might have discouraged countries from assuming the necessary costs to pursue their targets, since those initially high costs would not be justified if Kyoto requirements did not extend further into the future. This fear grew as 2012 approached especially when subsequent conventions failed to extend the protocol or replace it with any substantial agreement.

The Bali Action plan was launched by the UNFCCC in 1997, as a parallel track to address the post-2012 concerns. It was strongly expected, by the well-attended Copenhagen conference in December 2009, to have yielded another set of agreements that would succeed the Kyoto Protocol but failed in achieving this primarily due to some last minute unexpected objections. However, the Copenhagen Climate Conference did make some good progress in some respects, while failing at the binding consensus that had been anticipated. For instance, the Copenhagen Accord (COP. 15, 2010) sets a long-term bar of $2^0C$ maximum increase in average global temperature relative to pre-industrial levels, which has the advantage of setting a measurable goal, against which responsibilities can be apportioned and efforts can be weighed. Adopting a $2^0C$ bar is laudable, even though according to Hansen (2007) it might be an excessively generous threshold that is based on an underestimation of how much more warming the earth can accommodate before an irreversible threshold is reached. Copenhagen, at the very minimum registers a shift in focus from myopic climate-change combat strategies to a more long-term and assessable approach.

In addition, the Copenhagen conference established the Green Climate Fund, to administer funds, $30 billion between 2010 and 2012 and $100 billion per subsequent year, for mitigation and adaptation purposes in developing economies thereby recognising the need for developing countries' active involvement in mitigation efforts and their pledges of Nationally Appropriate Mitigation Actions (NAMA) and attempting to raise cognate enabling support and

monitoring for those nations' mitigating actions. It also established a framework called REDD which is an acronym for Reducing Emissions from Deforestation and Forest Degradation in Developing countries; a program aimed at tackling GHG emissions through Sustainable forest practices. Given these positive aspects and the fact that the Copenhagen accord was oriented towards emphasizing nationally-derived efforts rather than imposing restrictive global reduction targets, it was disappointing that the accord was only noted by the conference which failed to adopt it because of objections by Venezuela, Bolivia and Sudan (COP. 15, 2010). Confidence in the ability of international agencies to resolve global problems also suffered a great deal from this disappointment.

Due in part to the masterful chairing abilities of the conference chair, Mexican Foreign Minister Patricia Espinosa, and participants' fear of having another disappointing outcome, the follow-up conference to Copenhagen, which held in Cancun in 2010, successfully adopted the Cancun Document (Bodansky, 2011). However, a perusal of the UNFCCC (2010) COP. 16 document quickly reveals that it adds only very little to the Copenhagen proposal. It was legally binding on nations having been adopted, but offered very little clarity on how the Copenhagen goals and mechanisms such as the Technology Mechanism were to function. Perhaps the most valuable contribution of the conference in Cancun is its agreement to review the adequacy of the $2^0$C commitment and consider moving it to a $1.5^0$C bar as new scientific evidence became available (UNFCCC, 2010). To the extent that it gave force to Copenhagen proposals, with minor enhancements, and rejuvenated international confidence in global crisis resolution mechanisms, Cancun was a success. However, judged on the basis of its own substance and contribution to the struggle towards GHG reduction, the Cancun agreement added very little enhancement. In addition, the fact that it was unable to agree a second Kyoto-commitment period by the end of 2011 implies a failure which subsequent conferences would have to contend with. The subsequent exit of Canada from Kyoto commitments and its communication, along with those of Russia and

Japan, of disinterest in accepting a second Kyoto commitment period also severely dimmed the hope of a global consensus to seriously tackle climate change in the near-future.

The UNFCCC 17th conference of the parties was held on November/December 2011 in Durban, South-Africa, and achieved some modest results, most notable of which are: "the Durban Platform for Advanced Action", its call for all nations to negotiate a more ambitious treaty by 2015 that would take effect by 2020; its push for a second Kyoto commitment period championed by the EU but contingent on an agreement such as the Durban Platform; and a somewhat commendable attempt at operationalizing the Cancun agreements (It appears to have successfully agreed the details of roughly half the agreements ). All in all, it represents some progress and at least maps a way out of the current political stalemate that the expiration of Kyoto represents. It also won a huge success in attracting some support from the United States and other previously unsatisfied countries except Bolivia. It's failure however to agree a new accord to replace the Kyoto Protocol was further amplified by the exit of Canada's Conservative-party-led government from the protocol. The obvious reason for Canada's exit from the accord, the day after the Durban Conference, was the non-inclusion of major emitters such as China and India, as well as the possibility of Canada incurring huge inequitable fines of about $14 billion under the Kyoto arrangement (Kent, 2011), especially given its recent oil-sands exploration.

In 2011, the UNEP (2010) Emissions Gap Report estimates that developed and developing country pledges constitute only 60% of what is needed by 2020 to place the world onto a trajectory that will keep global temperature rises to less than 2˚C in comparison to preindustrial levels. This is assuming they all fulfil their pledges; an expectation which given the current framework, within which monitoring and compliance-enforcing infrastructure appear absent, appears to be wishful-thinking. The International Energy Agency (IEA 2010) also agrees with UNEP and estimates that the 2˚C goal will only be achievable with a "dramatic" scaling-up effort, particularly from major emitters. Against the backdrop of Hansen et al. (2007)'s more

recent research which indicates that a target of $2^0$ Celsius may prove ineffective, pledges may very well have to be more than doubled in order to achieve any mitigation success.

As the World anticipates the Doha Climate Conference in November 2012 (only a few months away), the question "Are we really serious about mitigating global warming?" is ever so pertinent. In 25 years, we seem to have moved significantly forward, given the many hurdles crossed each year. However, that movement becomes negligible once we gauge our progress from the point of view of our likely proximity to the precipice of global warming and the horrors it holds for us. The battle against global warming suffers primarily from uncertainty about estimates of global warming impacts, the long term nature of its manifestation, the apparent preoccupation of humanity with immediate economic gratification, and the suspicion most nations have of their "cheating competitors". It is apparent from our discussion in the previous paragraphs that international action on climate change has fallen short of minimum requirements indicated by science as necessary to forestall calamity. Therefore, we agree with Babiker, Jacoby, Reilly, and Reiner (2002) and others, who previously observed that there is a huge disconnect between targets set by the UNFCCC and its objectives. We–the majority of the world–seem to be serious enough to talk repetitively about global warming, but not yet enough to compromise our currently unsustainable lifestyles or bear some sacrifices.

Perhaps in time, trust would grow among nations and climate negotiations would start to accelerate towards meaningful measures. Or perhaps the world shall continue to play politics until irreversible thresholds are reached. In any case we cannot expect much progress unless our priorities are reorganized, we find ways of building trust in existing or new negotiation channels, and adopt holistic approaches[4] which further integrate current developing-world issues with the global-warming discourse. Then and only then can we decouple GHG emissions from economic

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[4] Such a holistic approach seems already to be in the offing, at least going by the emphasis of the recent June 2012 UN Conference on Sustainable Development in Rio (popularly called Rio+20), which approached climate change in the context of economic growth, sustainable development and underdevelopment.

growth and couple growth with energy security by putting an appropriate price on emissions and more aggressively investing in the research and development of renewable energy. In preparation for–and dread of–an impending catalyst that would reorganize global priorities, the only prudent thing to do is to work out the kinks of carbon pricing, and renewable-energy development… and keep talking.

## 2.2    Carbon Markets- A Global Survey

In this section, we present descriptive summaries of carbon markets around the world in order to give a sense of how they operate, their relative jurisdictions, and salient similarities and differences.

### 2.2.1    The EU ETS. Most of the information in this subsection was sourced from the European Commissions' official website (EU, 2011b) and more elaboration is accessible at http://ec.europa.eu/clima/policies/ets/index_en.htm. Where other authorities are relied on, we cite them as appropriate.

The European Union Emission Scheme (EU ETS) was launched in 2005 as a mandatory cap-and-trade program that allowed participants to buy and sell internally created emission allowances as needed, and also allowed permits sourced from the Kyoto Protocols JI and CDM schemes to be used for compliance purposes up to an agreed limit. It was the first emission trading scheme to be inaugurated in the world, remains the largest, and represents the EU's key effort to implement Kyoto's three mechanisms as part of its policy framework for combating climate change through cost-effective greenhouse gas reduction. The EU ETS covers $CO_2$ emissions in 27 EU countries and 3 other linked countries[5], straddling about 11,000 power stations as well as other industrial plants across those countries. These installations account for

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[5] Leichtenstein, Iceland and Norway

half of all EU emissions. Of all the other greenhouse gases, it only covers nitrous oxide emissions from certain processes (a recent development in itself) but is being planned to include more gases post-2013. It also initially excluded the aviation sectors of EU member countries before 2012.

The EU ETS is a legally binding scheme entered into by EU member countries, which are responsible for managing their own autonomous emissions trading systems in compliance with directives by the European Commission. Essentially, the scheme serves as a "community" of national schemes which facilitates cooperation among member countries towards meeting regional targets in a cost-effective manner.

At the beginning of a trading period EU emission allowances are grandfathered; a term which describes the allocation of allowances to companies, equivalent to their level of emissions in a specified base-year against which reductions are to be made. The EU ETS has a goal of reducing EU emissions in 2020 by 21% against a 2005 base year, and ensures this by reducing the emissions cap each year against the previous year. Its compliance aspect which mandates each company to submit allowances at the end of each year imposes heavy fines in the event of a short fall in allowances, and in order to avoid these fines, companies could buy from other companies who have an excess from savings made by lowering their emissions (relative to the base year) or support a CDM or JI project from which they earn Kyoto allowances. Companies with excess allowances might also bank those allowances in order to meet future compliance needs.

The EU ETS Phase II has been running for 5 years and is currently nearing its end. The first trading period–Phase I–covered the period from 2005 to 2007 and acted as the EU's pilot run of its Kyoto-influenced scheme, while Phase II covered the five year period from 2008–2012 for which EU countries were committed to Kyoto pledges. Phase III is currently being fine-tuned and should commence in January 2013 with many revisions made to its previous operations. Three very important modifications being planned for the third trading phase are: A change from primary allocation of allowances through grandfathering to allocation of 50% of these allowances

by auction[6], the harmonization of emissions caps to an EU cap across all member countries, and the adoption of a longer trading period. The switch to auctioning from grandfathering is supported by several studies such as those by Downing and White (1986), Millman and Prince (1989), Jung, Krutilla, and Boyd (1996) and Sorrell and Sijm (2003), which advise auctioning as the more effective method of allocating allowances in order to encourage technical innovation and tangible private investment in a low-carbon economy. Harmonizing emissions caps will, intuitively speaking, engender clarity and simplify policy-making, while adopting a longer trading period is likely to increase efficiency of the scheme by the reduction of uncertainty associated with rapidly changing regimes. In addition, member states shall be empowered in the third phase to exclude small installations with emissions below 25,000 tonnes of $CO_2$, many of which had been included in prior phases provided they satisfy some conditions. Documentation for the third phase has also agreed a decrease in annual caps by a factor of 1.74% relative to the phase II cap; this implies an average phase III cap of 1846 million allowances and an 11% reduction from the phase II cap. The EU envisages that 60–80% reductions in emissions, using a 1990 benchmark, would be necessary by 2050 in order to meet the $2^0C$ UNFCCC target.

The EU ETS has expressed eagerness in the past, to work with the US and other countries on cost and volatility reducing linkages which would mitigate climate change. In pursuit of this goal, phase III rules are planned to allow links to non-Kyoto entities insofar as they have mandatory cap-and-trade systems with a commensurate level of integrity, especially where those systems adopt absolute caps. Its recently announced linkage with the proposed Australian ETS in 2015 (see SMH (2012) for some details) is a step in this direction. As far back as 2007, the European Commission had, along with other parties created the International Carbon Action Partnership (ICAP) as a mechanism to support the linking of the EU ETS with other compatible trading systems (European Commission, 2007) and this partnership seems to be easing such

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[6] 88% of these allowances to be auctioned are to be distributed to member states based on their historical emissions, while the remaining 12% to be distributed will take cognizance of per capita income and prior Kyoto performance.

integrations, which have the potential of enabling cost effectiveness in the international crusade against climate change.

Allowances traded in the EU ETS include: EU Allowances (EUAs), Certified Emissions Reduction certificates (CERs), and Emissions Reduction Units (ERUs). EUAs are derived from local-EU generated mitigation efforts, CERs emanate from Kyoto CDM projects executed in developing countries, while ERUs are offsets from Kyoto JI projects executed in other developed countries. How much of Kyoto instruments can be used to satisfy compliance requirements varies widely, between 0% and 20%, among countries but roughly averaged 13% of the EU ETS annual cap for its second phase (Kollmuss, Lazarus, Lee, LeFranc, & Polycarp, 2010). The limitation of the use of Kyoto instruments is to ensure that they serve only as complements to internal abatement efforts within the EU, rather than a mere replacement.

The EU ETS has been the primary driver of the global emissions trading market and has become an archetype, despite its rapidly evolving structure, from which newer schemes borrow some lessons and features.


**2.2.2    The Australian carbon market.** Most of the information in this subsection was sourced from the Australian Governments dedicated Clean Energy Future (2012) website http://www.cleanenergyfuture.gov.au/clean-energy-future/our-plan/. Where other authorities are relied upon, we cite them as appropriate.

The Australian carbon market is only just starting to develop, having recovered from the country's parliamentary rejection of the Carbon Pollution Reduction Scheme (CPRS)–a pure cap-and trade system–in 2010, by revising the scheme into a more gradual format, which is being initiated by a carbon tax regime that eventually morphs into an ETS. This new scheme was a political compromise brokered by the Multi-party Climate Change Committee to accommodate divergent views within the coalition government on how to price carbon. Thus rather than dwell on the politically unfeasible CPRS, we proceed to describe the current scenario.

The Australian Government intends to reduce carbon pollution by 5 to 25% by year 2020, and 80% by 2050, below year 2000 levels. It intends to achieve this goal through two conjoint strategies described in its Clean Energy Legislative Package (2012): A Carbon Pricing Mechanism, and Clean Energy Future Programs. This combination, as well as other combinations of strategies, has been criticised by several researches such as Fischer and Preonas (2010), who asserted that such combinations result in policy interactions and are counterproductive. Our focus in this sub-section however, is on the carbon pricing component, which was legally enabled by the Australian parliament on November 2011.

The Carbon Pricing mechanism is composed of two stages: a fixed price period, and a flexible price period. The fixed price period started in July 2012, features a starting fixed price of AU$23, and is planned to cover three years ending in 2015. During this phase, liable firms can purchase limitless amounts of permits from the government at the current annual price which will be increased by a constant 2.5% in real terms in each following year. The second phase during which the emissions trading scheme will run, is planned for a July 2015 start. The ETS is intended to allow cost-efficient prices to be arrived at by the market while quantities are increasingly reduced in order to meet national GHG reduction targets. The rationale for the first stage–imposing a fixed regime–is to allow a smooth transition to an ETS. Given recent volatility of the EU ETS especially at its initial stages, the fixed price regime (which ultimately equates with a carbon tax) is an effort by the Australian government to regulate carbon price while the market is most vulnerable due to uncertainty.

The plan is designed to cover about five hundred companies[7] and local governments emitting above 25,000 $tCO_2e$ per annum in most sectors excluding agriculture and forestry. Emitters will be required to pay for each tonne of $CO_2$ they emit in order to purchase emissions units (permits), and surrender these at year end. If there is a deficit in surrendered units, they are

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[7] McGuirk (2012) of the Associated Press reports however that under the tax regime, only 294 large emitters were listed as liable by government, indicating that the scheme's actual coverage may be far smaller than generally anticipated.

assessed a charge. During the current phase, emitting entities simply pay AU$23 per unit required for compliance. The flexible-price phase is planned to be integrated with the EU ETS (SMH, 2012) and thus pricing within the Australian ETS should be very similar to the prices of EU CERs. Despite this link however, at least half of permits used by a liable company to meet compliance obligations must be generated within Australia. Kyoto permits (CDM and JI) shall be tenable for compliance subject to this restriction.

The planned Australian ETS is very similar to the EU ETS, ostensibly because it was fashioned after it, but perhaps necessarily so as a precondition for its envisioned integration with the European Scheme. However, it is planned to include some interestingly unique features; price ceiling and price floor. The price ceiling and floor will apply from July 2015 through July 2018, and during this period the ceiling will be set at AU$20 above anticipated international permit prices (probably as reflected in EU CER prices), while the floor will be set at AU$15 in order to prevent extreme crashes. Both will then be increased by 5 and 4% per annum respectively, to take account of likely price increase due to reductions in caps. The afore-mentioned anticipated integration with the EU ETS is also expected to be fully achieved by 2018 when these price limits will be relaxed.

Besides this federal scheme, Australia also has complementary policies at the state level, some of which involve the sub-national emissions trading scheme. This scheme is expected to collapse into the federal scheme, once its ETS is flagged off. The scheme is known as New South Wales Greenhouse Gas Reduction Scheme (NSW GGAS), which was extended to cover electricity sector emissions in the Australian Capital Territory (ACT) in 2005. Since the NSW GGAS scheme is very important, and is currently operational, we briefly describe its operation in the next subsection.

***2.2.2.1 New South Wales (NSW) Greenhouse Gas Reduction Scheme (GGAS).*** Most of the information in this subsection was sourced from the dedicated New South Wales Government official GHG website (NSW, 2012) and more elaboration is accessible at www.greenhousegas.nsw.gov.au. Where other authorities are relied upon, we cite them as appropriate.

The NSW GGAS is a mandatory emission trading scheme that functioned to optimize emissions within the state's electricity sector. It was inaugurated in 1997 through amendments to the state's Electricity Supply Act of 1995 as a voluntary scheme, but had since January 2003 become mandatory, thereby becoming the world's first mandatory carbon trading scheme. In 2005, it was expanded through local legislation to include the ACT. It was administered by the Independent Pricing and Regulatory Tribunal of NSW (IPART). IPART managed applications for project accreditation tendered by project developers, including their verification, while also enforcing the obligations of firms liable under the scheme and managing the Greenhouse Registry for registration and transfer of emission certificates. The scheme was closed this year in June 2012, with a final compliance date of 30 September 2012 by which all its participants must surrender their emissions certificates to meet their 2012 GHG benchmark, or face permanent forfeiture of those abatement credits for compliance purposes. As such, they could only be surrendered in the voluntary market. The NSW is currently in the process of winding up.

The scheme mostly covered emissions of 29 electricity retailers, but also includes four electricity-generators who directly sell to consumers. Some large consumers called "elective benchmark participants" also voluntarily opted to manage their emissions through the scheme- a unique trait in that it makes the scheme part-mandatory and part-voluntary. As of January 2012, there were 11 such voluntary participants. It is noteworthy that although the obligations were imposed on large retailers, the burden of reducing emissions (the cost) is ultimately shouldered by consumers. The scheme computes annual targets based on the year's established per capita

emission benchmark[8] (7.27tCO$_2$e in 2007) multiplied by the population of the region that year, multiplied by each liable entity's share of electricity sales (Kollmuss et al., 2010). In essence, the annual per capita emissions benchmark was fixed by the scheme, and on that basis regulated emitters derived their individual targets. This benchmark was also reduced annually in order to put an upward pressure on prices, and stimulate an incentive towards a low-carbon electricity sector.

Under the scheme, regulated entities could meet their emission reduction targets in two ways: Directly reducing their products' emission-intensities through enhanced efficiency in production and development of alternative low-carbon energy sources, or by purchasing accredited offset credits or certificates. The two acceptable offsets currencies for compliance are: the NSW GHG Abatement Certificates (NGACs) that are sold by those who surpass their own targets by increased efficiency or involvement in carbon sequestration projects; and the Renewable Energy Credits (RECs) that are derived from the separate national Mandatory Renewable Energy Target scheme. For participants who fail to meet their targets, a penalty is imposed which invariably serves as a cap on compliance costs for liable firms. This cap has been increased from the previous AU$15 level to AU$17 per tCO$_2$e for 2012 compliance (IPART, 2012), in view of the current level of the new federal tax which was set at AU$23 in June, 2012.

The current national plan is partly built on insights gained through the NSW GGAS and is designed to provide a broader coverage both in terms of jurisdiction, and controlled gases. In accordance with legislation however, the scheme had to be closed upon the commencement of a national ETS (NSW DWE, 2008). This was necessary in order to forestall duplication between the federal and state schemes, and to minimise costs for electricity consumers.

Some major problems that plagued the scheme included: double-counting of certificates due to the recognition of RECs which were also recognised in federal compliance schemes,

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[8] The sliding benchmark was also calibrated by the scheme's administrators to meet up with the country's 5% Kyoto obligation.

excess supply of certificates partly due to that REC recognition, and a high and largely ineffective emissions cap that proved insufficient in creating a price signal that couched an incentive to produce and consume in less carbon-intensive ways.

Notwithstanding its problems, the NSW government views the scheme's impact as considerable; 144,309,952 certificates were created over the lifetime of the scheme, translating into over 144 million tonnes of Carbon-dioxide equivalent emissions abated over its lifetime[9], primarily from coal-generated electricity. In addition, several frameworks in emissions measurement (particularly with respect to forestry), developed under the NSW GGAS have been adopted by schemes in the international community (including the EU ETS and the nascent Australian ETS), attesting to its role in culturing best-practices in ETS policy-making. It is also credited as having a strong legal and regulatory basis, and being the most cost-effective emission reduction policy in Australia, with a total abatement cost under AU$40 per tonne of emissions abated (Grattan, 2011).

**2.2.3    American carbon schemes.** The United States is generally perceived as being unconcerned about climate change due to its withdrawal from Kyoto and persistent rhetoric regarding the danger that such international agreements pose to its economic health. While this perception may be true of federal US climate policy, it is likely untrue at the sub-national level at which some effort–comparable to the best efforts elsewhere on the planet- seems to be increasingly made. In subsequent subsections, we describe two programs which represent significant effort at regional levels, to address GHG emissions[10].

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[9] Whether this translated into substantial abatement of emissions or not is an issue raised by Passey et al. (2007) who pointed out the absence of any additionality criteria in the recognition of projects used to generate emissions certificates. This implies that those projects may not have meaningfully reduced emissions below business as usual levels as presented by the scheme.

[10] A third cap and trade program, the Midwestern Greenhouse Gas Reduction Accord appears currently moribund probably due to the absence of political fillip after the last US elections saw some of its champions out of office. In any case, as the Centre for Climate and Energy Solutions

*2.2.3.1 Regional Greenhouse Gas Initiative (RGGI).* Facts and figures presented in this subsection are sourced predominantly from the RGGI official website (www.rggi.org) and details of the scheme can be accessed there. Other sources relied upon are cited as appropriate.

In 2005, governors of seven Northeast and Mid-Atlantic US states established the RGGI as the first multi-state mandatory cap and trade program in the US, in order to curb GHG emissions from fossil-fuel-fired electricity generation. Having expanded to a membership of nine states[11] and kicked off in 2009, the scheme has a goal of reducing $CO_2$ emissions from its member-states' collective power sector by 10% between 2009 and 2018. It also has a design which authorizes member states to auction 85% of their emission allowances to regulated companies that can then buy or sell among themselves depending on need, with the proceeds from the auction going to consumer benefit programs and strategic energy investments (RGGI, 2007).

Like the EU ETS, the RGGI houses individual emissions budget trading programs run by each member state, but unlike it the RGGI is itself a regional (subnational) scheme on a more modest scale[12]. The RGGI sets model rules which loosely guide each state's own rules and regulations governing its local electric power plants. For instance as a general rule, only plants generating up to 25 megawatts of electricity are included in regulation by the scheme. Regulated plants in a state are allowed to use allowances issued in a state to fulfil compliance requirements in that state or in any state within the RGGI. As such, the RGGI defines a regional compliance market for $CO_2$ that is composed of nine individually functional but integrated state markets. It differs, perhaps most significantly, from the EU ETS with its substantial auctioning of permits

(2012) observes, member states are no longer pursuing the scheme. It is also possible that the WCI was plagued by cross-border problems.

[11] Current members are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. New Jersey was previously a pioneer member but withdrew in November 2011.

[12] According to Damassa (2007) its member states account for about 10% (695MtCO$_2$) of US annual GHG emissions.

right from the onset, rather than the EU norm in which the bulk of permits are grandfathered with few to none auctioned.

Prominent features of its auctioning mechanism include: uniform-price auction format, single-round sealed bid format, quarterly auction frequencies and separation of non-identical[13] allowances into homogeneous groups. The RGGI also recognizes allowances for auction four years in advance of their generation, and sets a reserve price[14] for each auction. In monitoring the market, the RGGI cooperates with the US Environmental Protection Agency (EPA), the Federal Energy Regulatory Commission, and other federal agencies, particularly to detect market underperformance or price-manipulation by participants.

According to Kollmuss et al. (2010), the scheme prioritizes emissions reductions over offset generation–a very unique feature–since it allows offsets only as a limited compliance flexibility mechanism. Emitting facilities can only meet 3.3% of their compliance targets through submission of offset certificates; a requirement that is only mildly but increasingly relaxed[15] as the price of emission allowances rises beyond successive specified thresholds over a 12 month period. The obvious implication of this rule is that regional efficiency has to be improved in order to reduce carbon emissions and comply with at least 90% of the annual target. Cost-effectiveness is then brokered by firms that find it more economical to switch to low-carbon processes or alternative energy sources selling their saved allowances to those who find it costlier or less feasible. In effect, industry emissions within the scheme would be reduced at low market-derived costs. This is likely to be one of the most emission-intolerant markets in the world, since it caps its offset segment at less than 10% of compliance.

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[13] This describes the vintages of the permits. Permits can be used for varying compliance periods due to differences in the processes that generated them, and auctioning them all together would introduce pricing distortions since they would in effect be heterogeneous items.

[14] A reserve price is a minimum selling price below which an item will not be sold even to the highest bidder.

[15] The maximum percentage of offsets allowed per annum is 10%.

The RGGI is currently not linked to any other scheme. However, offset projects raised within a UNFCCC-compliant scheme outside the US shall be recognised and allowed for compliance (up to the limit earlier discussed) if the price of emission allowances reaches a certain threshold. This leaves open the possibility of a future link with the Kyoto CDM and JI mechanisms as well as others that may evolve. Four RGGI states–Maine, Maryland, Massachusetts and New York are also currently members of the ICAP, indicative of some association and collaboration with other global efforts.

The RGGI is a model–quite different from other models around the world–that adapts to the US "bottom-up" approach to the climate-change issue. Rather than being based upon some internationally-ascribed targets, it collaboratively derives its targets based on estimates of locally feasible reductions, from internal and federal stakeholders. Its stringent limitation of offset use for compliance purposes also stands out with both good and bad possible impacts. As Capoor and Ambrosi (2008) observed, the offset restrictions may cause liquidity problems and present a missed opportunity to access lower costs of emissions in the global market. On the other hand, it could help propel the efficiency of power-generation (including alternative energy research and development) within those states, while saving states from the onerous and expensive task of monitoring lots of offsets which emanate both within the states, and from different parts of the world. This second point is particularly important because under the scheme state-registries have a strict responsibility to monitor and verify all projects. With a large offset segment, that administrative responsibility may become cumbersome. Since the scheme is still relatively young, it remains to be seen how it shall evolve and what impact–as opposed to "expected impact"–it will have.

*2.2.3.2 Western Climate Initiative (WCI) and North America 2050 Initiative.* Facts and figures presented in this subsection are sourced predominantly from the WCI (2012) official repository    (http://www.westernclimateinitiative.org/component/    repository/general/program-

design/Design-Summary/) and details of the scheme can be accessed there. Other sources relied upon are cited as appropriate.

The WCI is a multi-jurisdictional program that organizes independent jurisdictions which work together on strategies and policies to address climate change issues in North America. Its members currently include four Canadian provinces (British Columbia, Manitoba, Ontario and Quebec) and the US state of California, after the exit of six other US states (Arizona, Montana, New Mexico, Oregon, Utah and Washington) at the close of 2011 (see Globe-net (2011) for news details). Several other Canadian provinces and states in US and Mexico participate in the scheme as observers.

The WCI is not yet operational as an emission trading scheme, although its first phase is scheduled to begin in 2013. Its specific protocols are still under development but some recommendations such as the selective regulation of entities that emit above $25MtCO_2$ only are published on its website. It has a goal of reducing emission in its member jurisdictions by 15% below 2005 levels by 2020 as part of its comprehensive plan, which also includes the development of clean-energy technologies and preparation for adaptation measures to address the impacts of climate change. It is also anticipated to cover nearly 90% of total GHG emissions in its partner states with a broad coverage of the electricity generation, transportation and industrial sectors, as well as residential and commercial fuel use. In addition, it is planned to be able to stand alone, be integrated into or work with federal programs that may emerge from Canada or the US.

The WCI appears similarly in concept to the RGGI scheme, despite its embryonic stage of development; Participants will each have a functioning state-regulated cap and trade system, which will issue allowances–just sufficient to meet its "annually-sliding" jurisdiction-specific emissions target–that are recognizable in other member jurisdictions for compliance purposes, thereby resulting in a regional allowance market. Its challenges may however be more complicated by its cross-country membership which implies geographical, climatic, cultural,

legal, commercial and particularly political differences that may prove difficult to harmonize in the face of conflicting interests among participants. These differences for instance are likely to have contributed significantly to the decimation of its ranks in 2011.

That said the WCI is unique in that it proposes three-year compliance periods, and features time-limitless allowance-banking. Since most other trading schemes to date run on annual compliance periods, and have expiry dates for tradable allowances, these features may make the scheme more flexible relative to others, giving participants the cost-reducing choice of how and when reductions are made. Its limited acceptance of offset allowances (maximum proportion set at 49% of reductions) from outside the scheme for compliance purposes may also help to assuage liquidity problems that may arise in future while putting pressure on the local facilities to invest in and develop low-carbon processes and alternative energy sources.

Summarily, the scheme appears to be a necessarily less stringent version of the RGGI model, which aims to achieve its relatively more ambitious goal of 15% reduction through opportunities accessible by breadth of coverage both in emission-sources and participants. For certain North American jurisdictions which require a less-stringent participation in climate-change mitigation than that of the RGGI model, it offers another bottom-up solution.

In 2009 the RGGI, the WCI and the Midwestern Greenhouse Gas Reduction Accord constituted the 3-Regions Collaborative primarily to share information and engage federal agencies on policy matters. This collaborative forum subsequently gave birth to the North America 2050 (NA2050) which is a non-binding partnership for progress open to North American jurisdictions, and committed to policies that facilitate low-carbon economic transition, enhance energy security, protect public health, and demonstrate climate leadership among its members. Given its origin and non-restrictive requirements, it is currently composed of twenty members, most of which are current or past members of the three regional bodies mentioned previously. For those jurisdictions that require an even less-restrictive framework than that of the WCI, this collective offers yet another avenue for participation in the global effort against climate

change. Notably, the six US states that left the WCI, as well as New Jersey (that left RGGI) are current members of the NA 2050.

## 2.3    Canada's Federal and Provincial Responses to Climate Change–Political and Economic Developments

Unless otherwise referenced, information presented in this sub-section is based on the official Government of Canada's (GOC, 2012) Climate Change website http://climatechange.gc.ca/default.asp?lang=En&n=4FE85A4C-1 and "Canada's Emission Trends 2012" an Environment Canada (2012) publication.

Since Canada has one of the three highest per capita rates of GHG emission, and currently accounts for about 2% of global emissions (Environment Canada, 2012), its efforts are relevant to global emissions reduction. Canadian efforts at battling climate change have been at two distinct levels: The Federal level and the Provincial level. At the Federal level, efforts are made mostly to ensure that Canadian interests are represented at international forums and that national targets are pursued, while provincial governments make autonomous but sometimes collaborative efforts to combat the problem in their respective provinces. Climate change policy in Canada is quite complicated due to its federal structure which empowers the federal government to negotiate terms, treaties and targets with the international community, but restrains it from unilateral implementation of those international agreements within the provinces. Therefore, pledges made by the federal government require the sanction and cooperation of provincial governments before they can be implemented within provincial jurisdictions. This fundamental feature is probably responsible in large part for some recent developments in Canadian federal and provincial climate policies. Perhaps federal efforts (which we shall discuss next), particularly international pledges and targets, cannot afford to be stringent because

enforcing such stringency is beyond the federal government's jurisdiction while natural resource control is within the jurisdiction of provinces.

**2.3.1 The federal picture.** Canadian Federal response in terms of legislation and policy, has gone through several phases, and is constantly changing due to the country's complex but interesting relations with the international community, its local politics, and the evolving composition of its local economy. Two considerations can be said to primarily drive Canadian climate policy: its growth plans, and the burden its climate obligations would imply relative to the burden shouldered by other nations. Canadian economic growth is currently predicated on its oil and gas exploration which is a predominantly high GHG-emitting activity. The fact that about 99% of Alberta's oil reserves come from its oil sands (Alberta Energy, 2012), which involve higher-emitting extraction processes than conventional crude, implies a very tight coupling of its growth-driver with increased emissions. Also, the fact that some economically-competing nations are excluded from carbon-reduction commitments has often been cited as a reason for not pursuing an aggressive carbon policy. When mixed with local and international politics, these drivers portend tension between the country's growth goals and its environmental goals–at least given currently available technology.

In comparison with the US voluntary-oriented climate policy bias, Canadian federal climate policy is hardly any more aggressive or ambitious despite the fact that the Canadian federal government has less political complexity to contend with, and far more institutional capacity to effect changes than the US. Save for its initial ratification of the Kyoto Protocol, federal climate policy in Canada has mostly emulated, and even trailed US climate policy. This is understandable given the close level of integration in markets across both countries under the North American Free Trade Agreement. Thus, the Canadian approach to climate change whittles down to a bottom-up strategic disposition that is very much akin to that of the US, but is slightly more federally-active.

At the 1997 UNFCCC conference in Kyoto, Canada agreed to cut carbon-dioxide and other greenhouse gases by 6% below 1990 levels from 2008 to 2012. However, this differed significantly from the subsequent announcement by then Minister of Environment Christine Stewart who, after meetings with provincial energy and environment ministers, proposed provincial GHG reduction targets of 3% below 1990 levels by 2010 (Smith, 1998). The obvious fact was that Canada was uncomfortable with the Kyoto target but had to agree to it under some international pressure at Kyoto, especially because in the months leading to the convention, the US had signalled support for a legally binding protocol and the Canadian government had boasted a more aggressive position than that of the US. Thus committing to Kyoto was motivated by a (face-saving) need to maintain the country's credibility in Climate Change leadership, rather than reflecting a federal-provincial consensus. Kyoto was thus seen at the provincial level as being a federal display of unilateralism in resource control issues, and a betrayal by the federal government (Smith, 1998).

The recent withdrawal of Canada from Kyoto late in 2011 makes quite some sense against this background. Since Kyoto itself forms the bedrock of international climate change policy and its target for Canada was not consistent with prior local consensus, its adoption in Canada was doomed from inception. Canada had also been unshackled by US withdrawal from Kyoto in 2001 and had openly expressed its lack of intention at meeting its Kyoto pledge for the past decade (see Governor General of Canada's (2007) Speech from the Throne). However, not meeting its Kyoto pledge translated into huge penalties that, according to Environment minister Peter Kent, would require payments up to $14 billion (Kent, 2011), to Russia and other Eastern European countries for Kyoto compliance permits. Withdrawal was therefore a necessary move. The environment minister also blamed the prior "incompetent liberal government" who signed the accord but made little tangible efforts at achieving it (Kent, 2011), reflecting the political undertone of the withdrawal from Kyoto which was seen as an ill-conceived liberal-party initiative that the conservative government had no intention of supporting.

Currently, the Canadian government claims support for any future international treaty that holds all major-emitting countries–including developing countries such as China, Brazil and India–responsible for GHG reduction. The Copenhagen, Cancun agreements of 2009 and 2010 respectively and the Durban platform of 2011, hold the promise of including binding commitments for high-emitting-developing-countries and so are currently favorably viewed by the Canadian federal government.

While its efforts at meeting international targets and deadlines have been generally lukewarm, the federal government has made some efforts at legislation and regulation of major industrial emitters which have stemmed the growth of its emissions profile–stopping short however at establishing a federal Emissions Trading Scheme or Tax. As inscribed in the Copenhagen Accord, the federal government has committed to an overall emission reduction target of 607 Mega-tonnes of $CO_2$ ($MtCO_2$) or 17% below 2005 levels by 2020 through a sector by sector approach that involves some cooperation with the US. The government also claims to have achieved half of this target in collaboration with the provinces.

Some examples of relevant federal regulations that are expected to contribute to its achievement of those targets are its GHG regulations for transportation and electricity sectors. Notably, the government created the *Passenger Automobile and Light Truck GHG Emissions Regulations*, the *Heavy-Duty vehicle and Engine GHG Regulations*, and the *Renewable Fuels Regulations (RFR)*. The RFR has been effective since December 2010 and requires an average renewable content of 5% in gasoline and 2% in diesel. In September 2012, the federal government also released the *Reduction of Carbon-Dioxide Emissions from Coal-Fired Generation of Electricity Regulations*, which takes effect from 2015 and imposes stricter standards on both new and obsolete coal-fired electricity generating units in terms of the carbon-intensity of their operations, and products. This regulation is expected to encourage electric utilities to transition into low emitting energy sources, but has been plausibly criticised by analysts such as Weis, Partington, Thibault, Gibson, and Anderson (2012) of Pembina Institute,

as leaving a loophole of three years within which new high-carbon coal-fired plants could be hurriedly set-up by utility companies. If this occurs, those plants will legitimately run for the next 45 years under the loose pre-2015 standards, and this could severely undermine national emissions reduction efforts.

In addition to the above regulations, the federal government has invested about $3 billion in the development of Carbon Capture and Storage (CCS) technologies by providing funding for up to six large scale CCS demonstration projects, while the government has also announced funding of about $27million for the Global Research Alliance's Agricultural GHG initiative through its Agricultural GHG Program (AGGP)[16]. The AGGP, designed to focus on mitigating agricultural emission of GHG, by bringing together farmers, the agricultural community and academia to collaborate on research, technology transfer, and beneficial management practices, seems to be showing some promise. However, the development of Carbon Capture and Storage technologies in Canada suffered a recent blow in April 2012 when major corporate participants in the first collaborative Alberta-based CCS–labelled *Project Pioneer*[17]–backed out of the scheme which had enjoyed both federal and provincial funding pledges (see www.projectpioneer.ca for an official announcement of this development). The federal government itself had committed $342.8 million, while Alberta provincial government had pledged $436 million to subsidize the cost of the project, which was estimated to be capable of eliminating one million tons of $CO_2$ per year. The huge subsidy and a largely positive feasibility study notwithstanding, the corporations decided to abandon the project, citing the low price-cap on carbon under the Alberta Carbon

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[16] Canadian policy at tackling GHG emissions is generally biased towards the generation of offsets through such schemes as CCS and AGGP, which emitters can fund in order to generate permits for compliance without necessarily adopting low-carbon processes in their industrial activity.

[17] Project Pioneer was a private-public large-scale CCS retrofit plant located at the Keephills 3 coal-fired power plant west of Edmonton and within 70 km of the Pembina oilfields. It was expected to sequester carbon as well as act as a channel for adapting some captured $CO_2$ to enhanced oil recovery. It is estimated to have the capacity to store up to 1 Giga-tonne of $CO_2$. The three major corporate stakeholders were Capital Power Corporation, Enbridge Inc. and TransAlta Corporation.

Pricing Scheme (Effective at \$15 per tonne of $CO_2$) and the insufficiency of guaranteed demand of $CO_2$ for oil-recovery purposes (O'Meara & Kleiss, 2012). Essentially, the current price of carbon is too low to make any CCS project commercially viable, even though the technology is viable and capital costs were reported to be in keeping with expectations in the project's feasibility study (Project Pioneer, 2012).

The foregoing again emphasizes the importance of carbon pricing in climate change mitigation. Innovations and research in Canada have been, and continue to be, discouraged in the absence of reasonable pricing of carbon, and all efforts towards mitigating climate change are meaningless outside the context of assured penalties for GHG emissions. Rather than invest huge amounts in risky projects, it is more convenient for the average emitter (an Alberta emitter for example) to simply pay a paltry \$15 per ton of carbon emitted into the CCEM fund. Arriving at a national price is not a current priority of the federal government (neither is it currently feasible for the politically-oriented reasons previously discussed and the economic/emissions diversity across the country), and so provinces are left to make individual efforts to achieve this by establishing markets either through taxes or trading schemes. The most remarkable of these provincial efforts which are still in the process of development at the moment shall be discussed in the next subsection.

**2.3.2    Brief survey of some Canadian provinces.** In this subsection, we briefly discuss some of the more remarkable efforts in five Canadian provinces with emphasis on market mechanisms. Most of the information upon which this subsection is based, is sourced from the official government websites[18] of the respective provincial regulatory authorities. Information from all other sources are attributed in-text as appropriate where used.

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[18] British Columbia: http://www.env.gov.bc.ca/cas/cap.html,
Ontario:http://www.ene.gov.on.ca/environment/en/category/climate_change,
Saskatchewan:http://www.environment.gov.sk.ca/,

In general, Canadian provinces that engage in a lot of resource-extracting activity or generate the bulk of their electricity from fossil-fuels have very high per-capita emissions levels, while those for whom resource-extraction plays a small economic role or for whom electricity generation is from water, natural gas or renewables have much lesser per-capita emissions. Examples of the former include Alberta, Saskatchewan, New Brunswick, Nova Scotia,[19] while Quebec, British Columbia, Manitoba, Ontario, Newfoundland, and Labrador are examples of the latter. Discounting environmental considerations (which is morally wrong of course), coal easily appears to be the cheapest source of energy, particularly in the provinces most endowed with them. Thus some strong public will, complemented by carefully-planned government policies, are required before such provinces can embark on significant transition from coal to cleaner sources, in meeting their power needs.

Emissions caps and targets across Canada are not defined in the absolute sense. Similarly to the federal preference for emissions intensity basis for mitigation, provinces also focus on intensity-reduction in order to engender growth-permissive mitigation[20].

**2.3.2.1 British Columbia (BC).** British Columbia is responsible for about 8.5% of total Canadian GHG emissions (Environment Canada, 2012) and was the first province in Canada to introduce legislation establishing a cap-and-trade scheme; perhaps partly motivated by its firsthand experience of some harsh phenomena attributable to global warming, such as the Pine-Beetle epidemic and the cumulative loss of half its snow pack (BC Govt., 2008). Most of the

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Manitoba:www.gov.mb.ca/conservation/climate/,
Quebec:http://www.mddep.gouv.qc.ca/changements/plan_action/index-mesures-en.htm.
[19] Alberta, Nova Scotia and Saskatchewan had the highest dependence on coal for electricity generation up until 2010; averaging a 50% ratio of their respective provincial coal to total generation capacity, with Alberta and Saskatchewan estimated to account for over 85% of coal-fired electricity in the nation by 2014 (Weis et al., 2012).
[20] See Table 1 in Appendix C for details on provincial pledges and implied standardized pledges. We use absolute figures in this computation (rather than intensities since according to Huot, Fischer, & Lemphers (2011), corporations are not likely to be able to effect significant reductions in their processes' emission intensity going forward, having tapped into recent one-off technological advances already (example cogeneration))

increase in BC's carbon emissions in recent years has been driven by the province's large natural gas projects and its per capita emissions stood at 12.4 tonnes while its absolute emission was 56 Mega-tonnes of $CO_2$e in 2010 (Environment Canada, 2012). The province was also the first North American state to introduce a "broad-based carbon tax". BC's Climate Action Plan, which was launched in 2008, specified a year 2007 emissions benchmark against which 33% and 80% reductions in $CO_2$ emissions are to be made by 2020 and 2050 respectively (BC Govt., 2008). The goal of the provincial government is to shift the economy from the production and consumption of carbon-intensive goods towards low-carbon goods, and it hopes thereby to reduce its carbon footprint (BC Environment, 2012). Government policies might have been responsible for the provinces reduction in emissions from 63 Mega-tonnes in 2005 to 56 Mega-tonnes in 2010, however the reduction may also have been due to the recession from 2008–2010 which occasioned reduced demand for natural gas.

The Climate Action Plan is based on several provincial acts such as the: Greenhouse Gas Reduction Targets Act, The Greenhouse Gas Reduction (Cap and Trade) Act, The Greenhouse Gas Reduction (Vehicle Emissions Standards) Act, the 2008 Utilities Commission Amendment Act, and the Carbon Tax Act. Since 2008 some other acts have been enacted to amend these acts. Two noteworthy Acts that in effect created the BC carbon market were the Carbon-Tax Act that was passed to encourage low-carbon economic development (with the generated tax revenue being applied as tax relief or subsidies for low-income households that might be unduly burdened by the tax), and the Greenhouse Gas Reduction (Cap and Trade) Act that gave legal support to the provincial Emissions Trading Scheme.

The Carbon tax was designed as revenue-neutral, constitutes a cap on the price of carbon within the province, and has risen by $5 each year (as stipulated by law) from $10 per tonne of $CO_2$ emitted in 2008 to $30 per tonne in 2012. Firms that embark on emission-saving or clean-energy projects could also receive tax rebates and this is meant to create an incentive for green business, and cut down on inefficient resource use. The tax has coverage over about 70% of BC's

total GHG emissions. The tax is described as revenue-neutral because proceeds from it are utilized directly in providing tax credits or cuts rather than accruing to the government as revenue. BC's carbon pricing model, which is yet to include carbon/emissions trading, has been much lauded and emulated in several other jurisdictions around the world (for example in Ireland).

Although the province has the legal basis to start emissions trading and was a pioneer co-chair of the WCI which it collaborated with other members to design, BC has decided not to implement a cap and trade system until it observes successful implementation and desirable performance of the WCI and the trading schemes in California and Quebec, especially as regards its effects on economic competitiveness and emissions reduction (BC Environment, 2012). Since California and Quebec are already in the process of implementing their respective state-schemes which shall both operate under the WCI umbrella, BC intends to monitor how those schemes and the WCI perform while relying on its tax instrument and other tools outlined in its inter- sectorial Climate Action Plan to deliver a lower-carbon economy in the short run. In the meantime, the province is grooming its fledgling offset scheme to meet with immediate carbon neutrality needs, and ultimate medium-to-long term export to the international voluntary and compliance markets.

BC is acclaimed for its public-sector's carbon-neutrality and renowned as a model of proactive climate action. BC's carbon-neutral regulation requires public-sector units to reduce and offset their emissions from vehicles and buildings, while cutting down on paper use. The public sector program is expected to yield carbon reductions of 36,500 tonnes, create new green jobs, and save organizations about $12.6 million per annum after full implementation (BC Environment, 2011). This move by the public-sector may have influenced private businesses, and may be responsible for the consistent reduction in general provincial consumption of fossil fuels since 2007, and the reduced the carbon intensity of the fuel consumed (through the renewable content legislation) despite the province's above-average post-recession economic growth. BC appears to be genuinely determined to make significant contributions to the global mitigation

effort by adapting its economy to sustainable cultural practices for both businesses and households.

**2.3.2.2 Ontario.** Ontario is the second highest absolute GHG emitter in Canada, second only to Alberta. The province emitted about 206 Mega-tonnes of $CO_2$–representing about 27.8% of total Canadian GHG Emissions–in 2010, but had a below-average per capita emission of 13 tonnes in the same year (Environment Canada, 2012). Due to its sheer population and high level of commercial and industrial activity, Ontario occupies a central position in Canada's efforts towards climate change mitigation.

Like BC, Ontario has a comprehensive Climate Change Action Plan. The plan lays out GHG reduction targets of 6%, 15%, and 80% below 1990 emissions levels by 2014, 2020, and 2050 respectively. The Ontario provincial government intends to achieve these targets through a number of programs reinforced by enabling acts such as the Green Energy Act (2009) that aims to expand Ontario's use of renewable energy, and its investment in, and development of, renewable energy projects and other green technologies such as electric cars. Also Ontario is reputed to be the first North-American jurisdiction to enact a regulation that phases out the use of coal in electricity generation. The province intends to achieve this phase-out by 2014, and it is estimated to reduce the province's carbon footprint from electricity by as much as 75%. The province has also invested about $11.5 billion in a regional electric public-transportation plan which also promises to help reduce emissions from the transportation sector.

Being part of the WCI, Ontario laid the legal foundation for a provincial cap-and-trade system in December 2009, by ratifying the *Environmental Protection Amendment Act (GHG Emissions Trading)*, and the *Ontario Regulation 452/09* both of which require emitting facilities to report their annual GHG emissions. The province is currently entertaining inputs from stakeholders in the design of a trading scheme that helps the province reduce emissions at lower costs, while being favorable to its industrial competitiveness. As part of complementary

regulations to support its trading scheme under the WCI, Ontario has also implemented the *Low Carbon Fuel Standards*, and the *Appliance Efficiency and Building Standards, and* has implemented a Feed-in Tariff as part of its *Energy Efficiency Standards*. Ontario clearly favors an ETS approach over a carbon tax, but is still far behind California and Quebec in its ETS implementation. Also, while there has been much talk about the introduction of carbon taxes especially at the last provincial election this has not materialized till date and is unlikely in the near future, given the province's sluggish recovery from the recent recession. Currently, provincial energy policy favors the application of subsidies to encourage "green efforts", rather than punitive measures such as a carbon price. Perhaps this absence of a carbon price in Ontario is itself partly responsible for the alleged failure of the government's green plans to achieve tangible economic and environmental gains in the province. However, the lack of thorough analysis and absence of coherent planning have been identified as major problems facing the renewable energy drive of Ontario Premier McGuinty, whose green electricity policies, according to Auditor-General McCarter, have wasted some $8 billion of Ontario taxpayers' funds and are unlikely to add significantly to net power generation (see National Post Editorial, 2011).

*2.3.2.3 Saskatchewan.* While its annual absolute emissions are easily dwarfed by those of British Columbia and Alberta, Saskatchewan has the highest per-capita GHG emissions among Canadian provinces. In 2010 it had per-capita emissions of 69 tonnes which is more than triple the Canadian average, and is mostly attributable to the province's oil and coal exploration and its carbon-intensive energy generation (Environment Canada, 2012). In May 2009, Saskatchewan adopted a GHG reduction target of 20% below 2006 levels as part of its Climate Change Plan. This target was an amendment of a prior target of 32% that was adjudged by the provincial government as being too costly for the economy. The revision was based on a study commissioned by the Saskatchewan Ministry of Environment and conducted by MK Jaccard and Associates (MKJA), which found that reducing the target from 32% to 20% would save the

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province about $65 million annually between 2010 and 2020, primarily due to the consequent reduction in compliance costs for electricity-generating and other industrial corporations (Saskatchewan Environment, 2009).

The province's main climate change legislation *The Management and Reduction of Greenhouse Gases Act*, provides for regulation of large emitters, specifies third party verification requirements, establishes a carbon compliance price schedule, and establishes a Technology Fund and Climate Change Foundation to fund research and development of low-carbon-intensity technologies, as well as emissions-abating technologies. The Act also provides for the establishment of an offset trading system to engender large emitters' investment in emissions-reducing activities, and creates a climate change office within the Ministry of Environment. Large emitters are defined as facilities emitting above 50 thousand tonnes of $CO_2$ per annum, and they are required to lower their emissions by 2% per year from 2010 to 2019.

The Saskatchewan approach to climate change seems similar in spirit to that of Ontario; while legislation has been made to enable the creation of an effective price on carbon, such a pricing mechanism does not seem to be aggressively pursued, but rather efforts are mostly channelled to "greening the economy" through public and private investment in green technology, while the province observes its performance in other jurisdictions. While it is prudent on some level to look before leaping into an ETS, it is highly probable that progress in Saskatchewan's green initiatives suffers seriously (in a similar sense as Ontario's) from the absence of the corrective tension that a punitive carbon price could create.

Saskatchewan is expected to adopt a carbon trading protocol essentially modelled after the Alberta ETS if and when it finally starts an ETS, but has not developed any protocols or concrete description of such a scheme. The two neighbouring provinces share many similarities. Like Alberta, Saskatchewan engages in carbon-intensive resource exploration, and produces most of its electricity by using coal. Like Alberta, Saskatchewan is unaffiliated with any regional emissions trading scheme. Also like Alberta, Saskatchewan is primarily interested in regulating

only its huge emitters, and has the capacity for generating offset credits through its agricultural sector. Thus it is reasonable to expect similarities between the carbon pricing policies of both provinces.

According to its Ministry of Environment's website, Saskatchewan is currently making efforts to develop quantification and verification protocols for offsets generated within the province. Saskatchewan is endowed with a large expanse of arable land and a huge agricultural and forestry sector. Since agriculture and forestry function as the major sinks for carbon, Saskatchewan might also profit immensely in the medium term by developing its offset sector in anticipation of future linkages with possible regional, national or global markets.

*2.3.2.4 Manitoba.* The government of Manitoba's official climate change website (Manitoba Climate, 2012) unequivocally supports the Kyoto Protocol, and embraces GHG reduction as an opportunity rather than an economic burden. Citing the Stern Review, the site champions early action as a strategic necessity for creating sustainable growth opportunities in future. Among other plans, Manitoba hopes to leverage its export of hydro-electricity to other jurisdictions in developing an offset market for future compliance requirements.

Manitoba joined the WCI in 2007, but still lacks the legislative authority to join in its emissions trading. However, it has adopted the Low Carbon Fuel Standards, and the Appliance Efficiency and Building Standards under the WCI. In March 2011, Manitoba started a Cap and Trade Consultation process in order to include inputs from stakeholders regarding the proposed structure and form of its carbon market, which is primarily built on the WCI framework. Also in tandem with the WCI's goal, Manitoba has a GHG reduction target of 15% below 2005 emission levels by 2020. Because Manitoba generates most of its electricity from water and is not among the provinces more endowed with high-carbon energy resources, its emissions level is below the Canadian average. In 2010, the province emitted an absolute amount of 20 Mega-tonnes of $CO_2$,

and had 16.3 tonnes per capita; the bulk of its emissions being from its transportation and agricultural sectors.

In June 2011 as a first step towards carbon pricing, the Manitoba Legislative Assembly passed the *Emissions Tax on Coal Act* into law. The law, which took effect beginning in January 2012, provides for the enforcement of tax rates ranging from $14.27 to $23.97 per tonne of coal depending on the carbon-intensity of the grade of coal, on anyone who purchased more than one tonne of coal within a calendar year (Manitoba Finance, 2012). This translates to a charge of $10 per tonne of $CO_2$ emitted across board. This regulation is expected to encourage a reduction in coal consumption, and support a transition to other cleaner sources of energy. While it is a step in the right direction, its coverage is too narrow, since coal is of relatively low use and exploration in Manitoba, and emissions from petroleum consumption and the province's agricultural sector are far more serious emission culprits.


***2.3.2.5 Quebec.*** Quebec has the lowest emissions per capita among Canadian provinces, with a figure of 10.4 tonnes per person in 2010 while its absolute emissions in the same year were about 82 Mega-tonnes (Environment Canada, 2012). The province established its first Climate Change Action Plan (CCAP), entitled Quebec and Climate Change: A Challenge for the Future, in June 2006.  Since then, it has revised the plan from time to time, notably in 2007 and 2011. In its initial form it consisted of 26 measures to reduce GHG emissions and adapt to the impacts of climate change. Regulations introduced through the plan covered various sectors of the economy, particularly: energy, transportation, municipalities, industry, natural resources, agriculture and forestry. Some of the prominent regulations were: Low Carbon Fuel Standards, Building Code Regulations (adhering to USA EPA standards), and provisions for a Carbon Levy, and a Cap and Trade system (Quebec MDDEP, 2011). In addition, the province launched its Electric Vehicles 2011–2020 Action Plan in 2010 to reinforce its commitment to the reduction of emissions in the transportation sector to which it had earlier committed $441.5 million in funding for the

expansion of public transit within the province. The province also mandated gas distributors to include a minimum of 5% of ethanol in their fuel sales by 2012 (Quebec MDDEP, 2011).

Quebec's carbon levy on fossil fuels was adopted in November 2007, and implemented retroactively to October 2007. It required 50 large energy companies to pay 0.8 cents and 0.938 cents for each litre of gasoline and diesel respectively distributed within Quebec. These rates are obviously too low to motivate behavioral changes in emitters towards GHG reduction, but the tax is still useful in its generation of revenue to fund government programs. According to CBC News (2007), the revenue generated by the tax amounts to about $200 million on average per annum. This provincial tax was also designed to increase by 1% each year between 2010 and 2013, and municipalities are allowed to levy an extra 1.5% within that same period, insofar as the proceeds would be used to ensure the sustainability of local public transit schemes (Quebec MDDEP, 2011).

Quebec joined the WCI in 2008. It is noteworthy that among WCI members, and indeed mitigation-oriented North American jurisdictions, Quebec has the highest GHG target of 20% against 1990 levels–far surpassing Canada's Copenhagen pledge as well (Environment Canada, 2012). In order to achieve this goal at the lowest possible costs–particularly in its industrial sector–the provincial government of Quebec adopted the *Regulation Respecting a Cap-and-Trade System for Greenhouse Gas Emission Allowances* which mandated the reporting of GHG emissions by facilities, established a local emission trading scheme, and also allowed the recognition of credits raised in other fully-compliant WCI jurisdictions in December 2011. This made Quebec the first Canadian province and the second North American jurisdiction after California to fully ratify participation in the WCI (Quebec MDDEP, 2012a).

Quebec's Cap and Trade system, as described under the regulation (Quebec Reg., 2012), is predicated upon the specification of a sliding cap on total annual GHG emissions of regulated entities. The cap on emissions shall be reduced by an amount between 1 to 2% each year from 2015, in order to gradually reduce GHG emissions. To enforce this cap, each regulated emitter

shall be allocated an amount of carbon allowances each year based on its historical emissions and production level. This allocation is by grandfathering–a mode of allocation that implies that government freely shares allowances rather than auctioning them. Every unit of emission by a regulated facility in a given year must be matched with an allowance, such that if the company emits more than its stock of free allowances, it is required to buy more to cover its excess either from government auctions or from other regulated facilities which used up less than their allocated stock. The penalty for default is equivalent to 3 emissions units or early reduction credits per missing emission allowance in a facility's general account.

The grandfathering of allowances is likely to be weakening to the effectiveness of the market, because it only penalizes the excess over historical emissions and may lead to an oversupply of allowances in the Quebecois carbon market as was the case in the EU ETS. Substantial auctioning of permits, which is an alternative approach to allocation, is a much more effective method because it penalizes every unit of emission, and thereby puts an upward pressure on the carbon price from the start. The EU itself, having learnt a hard lesson, has increased the percentage of auctioned allowances for its third phase. Auctions also provide revenue for government with which ameliorating programs, such as tax cuts for instance, could be funded as is the case with revenue from most carbon taxes.

Regulated emitters are defined in the regulation document (Quebec Reg., 2012)as any facility emitting at least 25,000 metric tonnes of $CO_2$ in a given year, and about 100 companies in the manufacturing and energy sectors are projected to fall under regulation. For now, the transport and construction sectors are exempt from regulation, but shall be included from 2015 onwards. A one-year trial period has commenced from January to December 2012, and companies are not obliged to meet their limits within this period. The cap effectively starts in January 2013.

Three types of allowances are recognised in the market: early reduction credits, offset credits, and emission units. Early reduction credits are credits given for qualifying reductions in GHG emissions between January 2008 and December 2011. Offset credits are generated mainly

from $CO_2$ sinks rather than internal emissions savings, and are acceptable for compliance only up to a maximum of 8% of a facility's total emissions within a compliance period. Emissions units are the primitive allowances allocated to emitters at the beginning of the year, or auctioned sometime during the year by the provincial government. In addition to these, all credits raised by another jurisdiction with which Quebec has an agreement such as that of the WCI are eligible for compliance.

The minimum price of each emission unit is set at $10 for auctions in 2012, and increased by a percentage of 5% for each subsequent year. By 2020 therefore, the minimum price shall be $14.77, and serve as a price floor.

According to the regulation (Quebec Reg., 2012), auctions of emissions units within the cap for a year that are not allocated may be conducted up to a maximum of four times a year. These auctions will be organised as single-round sealed bids with the maximum total by any individual emitter set at a maximum of 15% of the total units available for auction in 2013 and 2014, and 25% for 2015 and subsequent years. The bidding progresses from a high price with the highest bids being awarded first until all the units have been sold at successively lower prices, or the minimum price is reached. At the end of the auction, the Minister determines a settlement price (a uniform price) that must be above the applicable minimum price, and corresponds to the lowest bid for the last lot of emissions awarded. Proceeds from auctions are to be paid into the provincial Green Fund, and any unsold permits are to be kept for sale in the next auction. If such units are still unsold after three years, they shall be moved into the government's reserve account.

Apart from auctions, the government may also choose to sell emission units by mutual agreement up to a maximum of 4 times in a year. Sale by mutual agreement involves the sale of units from the government's reserve account at pre-2014 prices varying from $40 to $50 depending on the category of units. After 2014, the prices shall be increased by 5% annually. This method of sale is planned to help ease periods of shortage in emissions units and prevent price bubbles. Its proceeds are also to be paid into the Green Fund.

Quebec recently published an amendment to the regulation in June 2012 with the purpose of harmonizing its local system with California's and the potential markets in British Columbia and Ontario (Quebec MDDEP, 2012b). The central design of the market as outlined above remains unchanged, with most of the amendments representing clarifications or corrections to reduce ambiguity. The amendment also clarifies specific rules under which offsets will be recognised among other issues.

## 2.4    The Alberta Carbon Market- Salient Features

Unless otherwise referenced, information presented in this sub-section is sourced from the official Government of Alberta Environment and Sustainable Resource Development webpages at http://environment.alberta.ca and http://environment.alberta.ca/02275.html.

Alberta is easily the largest GHG emitter among Canada's provinces and territories in terms of absolute emissions, and ranks as the second (to Saskatchewan) in per-capita emissions. In 2010, Alberta was responsible for about 34% of total Canadian GHG emissions[21], and firms emitting above 50 $KtCO_2$ within Alberta were reported to emit a sum up to about 122.5 $MtCO_2$ which is about 47% of total Canadian GHG emissions by firms above the same threshold[22] (Environment Canada, 2010). The two major drivers of Alberta's emissions are its oil and gas prospecting activities and its coal-fired electricity generation sector, although other sectors such as chemicals, fertilizer production, and agriculture contribute a modest amount to the province's emissions profile. Coal, in particular has a high GHG-emissions intensity of over 1050 tonnes of $CO_2$ for every Giga-watt-hour of electricity generated which amounts to about 20 times the intensity of other sources of electricity generation. In 2009 alone, coal-fired plants accounted for

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[21] See Table 2 in Appendix C for a breakdown of total emissions contribution by province.
[22] See Table 3 in Appendix C for 2010 reported facility GHG emissions (>50$KtCO_2$) by province. Alberta's 47% contribution in Table 3 should not be confused with its 34% contribution derivable from Table 2, because Table 2 reports total emissions from all sources while Table 3 presents emissions from facilities that emit 50$KtCO_2$ or more annually and are required to self-report to the federal government.

almost 75% of electricity generated in Alberta (the highest among Canadian provinces), with the balance mainly generated through natural gas (Statistics Canada, 2012). The coal-fired percentage is likely to increase significantly as demand for electricity in the province continues to rise due to increase in population and industrial activity, while access to alternative energy remains prohibitive. In addition, Alberta holds the bulk of Canadian oil reserves, and produced about 1.4 million barrels of oil (synthetic crude and heavy oil combined) per day in 2010. Its production of synthetic crude oil is projected to increase by about 60%, while its heavy oil output is projected to witness a 170% growth relative to 2010 volumes by 2020 (Environment Canada, 2012). These are pointers to the tight coupling of Alberta's economic growth with rapid emissions growth, as well as the province's importance to Canadian GHG reduction efforts.

In 2002, Alberta took the initiative of developing the first provincial Climate Change Action Plan in Canada and passed the Climate Change and Emissions Management (CCEM) Act in 2003 as an enabling legislation. Among many provisions, the Act required industrial facilities with emissions over 100 kilo-tonnes of $CO_2$ per year to file a report of their emissions on an annual basis. This legislation was further bolstered by an amendment through the Specified Gas Emitters Regulation (SGER) in 2007 (Alberta Environment, 2007), which required each of those large emitters to reduce their emissions intensity by an incremental 2% per year up to a target 12% between 2007 and 2014, relative to a baseline average of emissions in 2003, 2004, and 2005. This roughly translates to an intensity reduction of 2% per year for regulated facilities. As at the time, approximately 100 companies within the province qualified as large emitters[23], and the largest of these were oil and electric-utility companies. Notable among these emitters were corporations such as TransAlta, Alberta Power, Capital Power, Syncrude, and Suncor which were reported by Environment Canada (2010) as five of the largest emitters in Canada in 2010, and had

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[23] The number of large emitters seems to have declined from 100 corporations in 2007 to 58 companies in 2010 (Environment Canada, 2010), although the data-set relies on self-reported emission information and raises the possibility that not all corporations that actually qualified were included.

huge qualifying operations in Alberta. Goddard et al. (2008), reports that the largest 30% of regulated firms in 2006 were responsible for about 87% of emissions by large emitters in Alberta. Data from Environment Canada (2010), also suggests that the top 6 emitters in Alberta (5 of which we previously named), constituted the top 10% of regulated corporations in 2010 and contributed about 61% of total emissions by regulated emitters in that year. One implication of this type of market distribution where a few participants appear dominant may be the manifestation of power laws; a market constituted by Alberta's currently regulated emitters may display an oligopsonistic structure due to the high concentration of the market's demand side.

Recognizing a need for flexibility, and in an attempt to avoid stifling concerned corporations by the new compliance requirement, the provincial government specified 3 alternative ways by which large emitters could meet compliance requirements in the event that they fail to reduce the emissions intensity in their respective facilities below the required threshold: Emitters could purchase Emissions Performance Credits (EPCs), Emitters could purchase Verified Emission Reductions or Removals (VERRs) that are also called Alberta-based Offset credits, or they could pay $15 (per $tCO_2e$ emitted) into the Climate Change and Emissions Management Fund (CCEMF). EPCs are credits that are offered for sale by a regulated firm that is able to reduce its operational emissions during the year, and can sell the credits it thereby saves to firms that exceed their allowance targets for the year. VERRs are offset allowances that are raised through certified and verified abatement projects outside regulated facilities, which either capture carbon from the atmosphere or prevent a release of carbon into the atmosphere that would have occurred in the absence of the project. The third option is for companies to simply pay a legislated amount of $15 for each tonne of GHG emissions that exceeds their target in a year, and this option effectively serves as a cap on the price of carbon in the province. A question that we hope to resolve in this study is whether the proliferation of compliance sources adds to the performance or health of the market. It would also be interesting to know if the stipulated contribution to the CCEMF per unit of $CO_2$ makes a difference to market performance.

The Alberta CCEM Act in combination with the 2007 SGER, created a market for carbon by putting a price on emissions within the province and establishing reduction thresholds. It represents one of the earliest responses by countries and other jurisdictions across the world to the Kyoto Protocol. Whether or not the market has succeeded in arriving at an effective or efficient price in the past five years is an issue that incorporates the political economy of the province, the consequent relative ambition or lack of ambition of the province's climate change targets, and the market's structural design.

Since the nature of emissions in Alberta is peculiar in that a significant chunk of its emissions is released by its energy sector, the Alberta approach to climate change mitigation is necessarily energy-sector emphatic. Thus most of its regulated companies are oil and gas companies or electricity companies, with a smattering of fertilizer, chemical, and forestry companies involved. However, the oil sector is also the cornerstone of Alberta's economy today, and is the livewire of much anticipated growth within the province. Therefore it is only predictable that the regulatory authorities would be under pressure to protect the sector from potential growth-inhibiting policies that may reduce its global competitiveness. Similarly, increased compliance cost for electricity-generating corporations will necessitate increased electricity prices in the province. Given that utility companies are constrained by government-imposed electricity price caps, the introduction of stringent policies may conceivably injure the required growth in investments in those utilities that is a prerequisite for meeting the fast-growing consumption of electricity in the province and averting a power crisis. Thus the fundamental dilemma in the political economy of Alberta's climate change action appears to be embodied in a choice between "climate-injurious growth" (with its many attractive benefits), and "growth-injurious climate stewardship". The benefits of economic growth will serve Alberta's own local desires well and perhaps trickle across the rest of Canada, while climate-responsibility through stringency will serve the entire globe including Alberta. Since the cost of serving the entire globe in this dilemma requires personal sacrifice, and provinces as well as countries are primarily

competitors, it is only logical that there will be hesitancy in pursuing an aggressive climate change agenda in Alberta.

The above dilemma is stated in a polarized manner with mutually-exclusive choices to emphasize the tension between provincial wealth, and climate responsibility. In reality, the province can adopt policies that balance both goals, by pursuing economic growth in a less aggressive manner than it would have, while exploring technology that can put such growth on a low-carbon trajectory. According to scientists like Lawrence and Schelnuber who spoke at the recent Robert Bosch Stiftung (2012) public podium discussion on climate change mitigation, such technological breakthrough is likely to take at least another decade to become economically viable.

Alberta's homegrown solution towards tackling the dilemma is its establishment of an offset system in which other unregulated sectors of the economy (particularly agriculture and forestry) are encouraged to participate by voluntarily implementing projects that reduce the level of emissions that would have occurred under business as usual scenarios, or embarking on projects that capture carbon from the points of production (that is Carbon Capture and Sequestration (CCS)). These projects go through a series of verification and certification procedures based on Government of Alberta approved protocols in order to ensure that they are authentic and meet additionality and permanence criteria[24]. The Government of Alberta claims on its official Agriculture and Rural Development webpage (Alberta Agric., 2012) that of the 29 $MtCO_2$ carbon-reduction achieved by the province between 2007 and 2011, over 58% was achieved through offset generation, and  that market participants are increasingly relying on offsets as a cheaper alternative to making payments into the CCEM Fund. As at 2007, regulated firms as a whole met 47% of their compliance obligations by paying into the CCEM Fund, 30%

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[24] Additionality requirements in Alberta imply that projects must be real, demonstrable, quantifiable, and not required by law (Alberta Environment, 2007). The concept of permanence has to do with an assurance that a unit of carbon abated will not eventually be released into the atmosphere after credit has been given for it. These two features are germane to maintaining environmental integrity in any emissions trading scheme.

through internal process improvements, 18% through VERR (offsets) procurement, and 5% through EPCs (Alberta Agric., 2012). The relative magnitudes of compliance methods had evolved by 2011 when payments into the CCEM Fund decreased to 32%, internal process improvements accounted for only 13%, EPCs accounted for 9%, while VERRs increased to 46%[25] of emissions reductions (Alberta Agric., 2012); demonstrating the increased role of offsets in the compliance mix. As of 31st August 2012, a total of 127 offset projects were reported to have been registered by the Alberta Emissions Offset Registry, with 24,566,949 VERRs having been registered by that date (EOR, 2012).

Thus, the Alberta strategy for combating climate change is more focused on offsetting emissions (although not exclusively), rather than the aggressive reduction of its production or use of fossil fuels that presents very high opportunity costs especially from a resource-endowment perspective. The offset approach to climate change mitigation has been severely criticised by environmental activists such as George Monbiot who articulated one of two popular criticisms in a 2006 Guardian newspaper publication (Monbiot, 2006). His criticism was that offset systems have a tendency to frustrate genuine efforts at abatement. Since firms are allowed to buy cheap offsets for compliance (offset prices are generally very low in most jurisdictions), they may tend to continue production in a business-as-usual manner or even choose to increase their emissions rather than adopting any behavioral changes towards a low-carbon economy. Invariably this may translate to a lot of motion and little movement, creating a scenario in which it appears that a lot is being done to curtail global warming whereas there really is no mitigation.

A second criticism is that offset systems place excessive monitoring, and verification responsibility and costs on government and where these are not properly done, offsets credits may be issued without abatement actually occurring–thus defeating its purpose as a mitigation tool. To further exacerbate this problem, project developers have been reported to generate offset credits

[25] Prior to 2011, Agricultural Tillage was the major offset allowance registered by the Alberta Carbon registry, so the boost in 2011 reflects the incorporation of other types of projects such as biogas and forestry (Alberta Agric., 2012).

through fraudulent or unethical means. In China for instance, some project developers deliberately engaged in the production of HFC-intensive refrigerants in order to earn offset credits for destroying the ensuing emissions, while in Nigeria, where gas flaring is a criminal act by legislation, Agip Oil previously had a brazen plan to generate electricity from the natural-gas it constantly flares and tender this to credit-awarding agencies as offsetting activity worthy of reward (Muskerjee, 2009).

In Alberta, this globally pervasive concern about weak standards for offsets recognition was amplified by the province's Auditor General in 2011 (see CBC News, 2011). In January 2012 stricter quantification and verification standards were imposed on offset generation within the province, possibly in response to the provincial Auditor-General's comments in his audit report of the previous year. In that report, he had blamed the poor performance of the scheme on ambiguity of rules and regulations governing the quantification and verification of offset projects. However, despite acknowledging the regulatory improvement of the scheme in November 2012, the auditor general still expressed skepticism on how much could be achieved given the quantification and verification ambiguities that were unresolved (see Cryderman, 2012). Also, the recent development that we previously discussed in which the 3 corporate partners of the Project Pioneer CCS backed out, is a major setback to the offset scheme is Alberta. Apart from the lack of stringent standards in the scheme's measurement and verification protocols, the absence of a price that reflects the high social cost of emissions is bound to be at least as much of a major obstacle to the offset segment of the Alberta Carbon market as it is to the other segments that emphasize efficiency in production. The cancellation of that project also sends a negative signal to potential investors about the high risks of investing in that sector.

While these criticisms are plausible, the Alberta carbon market is also endowed with a few features that may yield tangible benefits once complemented with a portfolio of other policies with similar consistency, as well as more stringent standards regarding quantification and verification of facilities' emissions and projects within its offset segment. For instance, the

market is designed as a closed market within which only Alberta raised allowances (whether EPCs or VERRs) can be tendered for compliance. In the absence of the province's low price cap (that is the $15 CCEM Fund cap), this feature has the benefit of stimulating growth both in production efficiency among regulated corporations and in the offset segment where unregulated participants can contribute to mitigation efforts. The closed design ensures that abatement activity actually has to occur within Alberta, rather than Alberta corporations getting to pollute more by buying up allowances raised by abatement efforts elsewhere.

The implication of this feature is that Alberta can learn to grow and develop its economy on a sustainable low-carbon path, which could present significant and strategic competitive advantage in the future. In addition, particularly regarding offsets, this feature reduces the burden and cost of verification to the vicinity over which the provincial government has existing monitoring infrastructure. In essence, the feature allows for a simple market that can be observed and nurtured pending maturity, by which time it could be robust enough for linkages with other markets. The main benefit then for opening up the market will be to tap into its comparative advantage and broker an avenue for the sale of Alberta-raised VERRs as a viable export.

Another remarkable feature of the market is the inculcation of key enablers in its offset system. As opined by Goddard et al. (2008), there are two key enablers in the market: Climate Change Central (A non-governmental organization) and the various project aggregators who accumulate small projects (mostly from the agricultural sector) and package them as bundles for sale to large emitters. These two participants have contributed to the bottom-up development of market standards and protocols, and facilitated the functioning of the market. Climate Change Central (C3) plays a useful role by creating a forum that encourages discourse among stakeholders (which include regulators, project developers, aggregators, and researchers), and collaborating with Alberta Environment in running the offset registry, thereby providing adequate oversight for the market. Aggregators solve the problem of matching tiny bits of offset projects by small project developers (farmers for instance), with huge emitters. In essence they

intermediate by matching supply with demand and create magnitudes of credit bundles that are sufficient to interest the demand side. This has encouraged both farmers and regulated corporations to participate in the market while eliminating the burden of market propulsion that government would have had to shoulder.

In summary, while the market still has a long way to go in the development of quantification and verification protocols, it seems to be on the right track; experiencing teething problems as would any other nascent market. However, the market is severely plagued in other respects which are likely to manifest negatively as time goes on. One of the major defects that we perceive in the market is the $15 price cap imposed by the CCEM Fund which is far below the cost of most types of large-scale offset projects such as CCS projects (IMC Report, 2008). While a safety-valve price cap is necessary to dampen volatility, placing it at such a low level is likely to discourage investments in the offset market where marginal costs for large projects are estimated to vary realistically between $50 and $300 (IMC Report, 2008). The low effective cap might therefore explain most of the market's current inability to kick-off with energy, since it may be crippling supply.

Another fundamental defect is the laxity of provincial reduction targets in concert with the province's adoption of an intensity-based definition of large emitter's annual targets. Alberta's target by 2020 is to emit 50 $MtCO_2$ below "business as usual" (BAU) levels (recall that even close neighbour Saskatchewan has a 2020 target of 20% below 2006 levels). This registers as a very unambitious target since based on data from Environment Canada (2012), the BAU level by 2020 is expected to be 285 $MtCO_2$, and a reduction by 50 $MtCO_2$ still puts the province at a level of 235 $MtCO_2$ that exceeds 2005 levels by about 4 $MtCO_2$. In essence, Alberta does not intend to reduce its emissions in the next few decades–it actually plans to increase it. This lack of an aggressive GHG-mitigation policy becomes even clearer when we consider the fact that Alberta climate policies employ a 2003 - 2005 benchmark, rather than the generally lower 1990 levels that are more widely used as benchmarks (for example 15% and 20% below 1990 levels

are the targets adopted by Ontario and Quebec respectively (Environment Canada, 2012)). Relative to 1990 emission levels, Alberta's target pales significantly and even implies a 16% increase in emissions against 1990 levels by 2050 (Huot et al., 2011). This is not far from independent observations by researchers at Cambridge Energy Research Associates (IHS CERA), who were reported as noting that an average global carbon price of $20 will still cause a 26% rise in emissions by 2030, and an effective price of at least $60 will be necessary to achieve a drop of 22% by 2030 (Environmental Leader, 2009). Given that there is an international consensus that global warming should be kept below $2^0$C in order to avert cataclysms[26], and it is widely agreed that GHG reductions of 60–80% against 1990 levels would be necessary to achieve that goal[27] (EU, 2011), Alberta's climate policy blatantly contravenes global consensus on what is required.

In order to add fillip to the carbon market and enable it to grow, the Alberta government may need to exert some pressure in terms of more ambitious targets that would translate into more reductions in GHG emissions by individual firms. Also, the use of a 2% annual intensity reduction target at the corporate level encourages ambiguity about how much emissions is actually abated while it is likely to be too low to stimulate much tangible reduction in emissions. Together, these two aspects of the carbon policy design are likely to severely undermine the market, and cast Alberta as a progressively high-emitting source of carbon rather than as a jurisdiction actively crusading to mitigate it.

Certain questions regarding the design of the carbon market in Alberta remain unresolved, and have not really enjoyed much discussion and analysis in the literature. We proceed to highlight some of these as our research questions for investigation in the next chapter, and make some efforts at tackling them in subsequent sections.

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[26] Recall that some prominent scientists such as Hansen (2007) think this threshold is itself too risky.

[27] Weaver, Zickfeld, Montenegro, and Eby (2007) make a very compelling analysis that indicates that only targets of 90% reduction and above would suffice in keeping global warming below the $2^0$C threshold by 2050, and even then complementary measures such as direct atmospheric capture and sequestration of $CO_2$ would be necessary.

## Chapter 3: Research Questions

We present our research questions in brief here and further develop them in section 6 where experiments are discussed in more detail.

### 3.1    Research Question 1

*What are the likely effects of the sources of carbon credits on volumes of trade and prices? Should the Alberta ETS include both EPCs and VERRs or just one of them? If only one source should be included, which should it be? Also is there any gain from the added complexity?*

We differentiate and contrast among markets where:

a) Regulated emitters alone generate both demand and supply of credits and no external players are involved [only EPCs sold];

b) Regulated emitters don't supply (No EPC) and only project developers do [only VERRs sold] and;

c) Both Regulated emitters and Project developers supply credits to the market [EPCs and VERRs sold]

### 3.2    Research Question 2

*What effect would an increase in the number of emitters covered have on the effectiveness and efficiency of the market? In essence will a bigger market yield better performance?*

As specific scenarios, we explore 2 separate cases of regulatory coverage which capture 500 and 1,000 emitters respectively. In a practical sense, our aim here would be to understand the effect that imposing a more stringent qualification measure (significantly less than $100MtCO_2$) will have on attaining the governments' reduction targets.

**3.3     Research Question 3**

*How do alternative market pricing mechanisms compare in terms of their effectiveness at abating emissions?*

We investigate this question by examining 2 types of multi-unit auction designs (Uniform-Price Auction and Discriminatory-Price-Auction), and compare the results from these.

Federico and Rahman (2003) examined prices and returns in comparing uniform and discriminatory auction pricing mechanisms under perfect competition and monopoly and find that they differ significantly only in the monopoly case. We expect to see some difference in these two mechanisms since our market specification lies somewhere in between these two extreme market structures.     Comparing the two mechanisms, Rassenti et al. (2003) found from an analytical experiment that switching to a discriminatory mechanism from a uniform-price mechanism engenders significant electricity price increases, while price variations are lower for a discriminatory system than a uniform price system (given excess supply). On the other hand, Evans and Green (2003) find such a switch to have a depressing effect on prices in the electricity market of England and Wales. Bearing in mind that while high prices connote a negative phenomenon in electricity markets from a social perspective, they are necessarily desirable (up to a point) for an emission-reduction market, the foregoing is at least indicative of some debate as to the effect that alternative pricing mechanisms may have on market behavior.

We hope to explore the differences in trading volumes and price levels (if any) among these 2 market designs.

**3.4     Research Question 4**

*What range of levels of the CCEMF contribution would be useful in stemming volatility without stifling the effective price for the Alberta Carbon market?*

We shall address this question by examining the nature and range of price variations in the market while exploring the 3 questions highlighted above.

**Chapter 4: Methodology**

Traditionally, economic models of markets are based on reductionist assumptions in pursuit of tractability, and as observed by Farmer and Foley (2009) our most prevalent models in contemporary policy-making are either of the Econometric or at best the Dynamic-Stochastic-General-Equilibrium (DSGE) variety. Both of these as well as myriads of DSGE variations upon which the insights of the New Neoclassical Synthesis (see Clarida et al. (1999), Woodford (2009)) are built, have been shown in the light of recent occurrences in the global economy to be largely inadequate in understanding, or predicting extreme events, neither have they been useful in meaningfully prescribing a way out of recent financial crashes (see Stiglitz (2011), Krugman (2011), and Mitchell (2009)). Econometric models assume macro-level behavior without consideration of how that behavior is generated. Such neglect may be trivial for static systems, but becomes costly when the system or unit being studied has a dynamic and adaptive nature. While the DSGE improves upon Walrasian macro-econometrics by attempting to construct micro-foundations for a new macro-perspective, it falls into some age-long traps through its fundamental assumptions such as: rational expectations, perfect markets, and representative agents which have been shown to be unrealistic by empirical surveys (see Colander (2006), Campbell (2000) and Stiglitz (2011)). During bubbles and crashes which are actually not as rare as one would expect, these equilibrating features are wont to be absent, and their absence renders the models impotent. Of course, these periods of extreme market fluctuations are only the periods when we see the failure of those model; they probably only "appeared" to work when the economic system was stable. Nonetheless, while these models falter in explaining economic systems, they have been useful in understanding some basic linear interactions among economic variables which have been empirically validated in the past, and have added helped solve many comparative-static problems. The problem is that the real world is in a state of constant flux.

The failure of these types of models informs our interest in Agent Based Models which enable us to examine the market as a complex evolving system. Since our intent is to examine

scenarios within an existing market, realism is of utmost priority to us and previously elegant economic models such as those already mentioned are unlikely to yield any valid insights. Therefore, we avoid using them because we know a priori that the carbon market in Alberta is not a perfect market (it shows elements of market concentration on both the demand and supply sides), that agents operating in the market are substantially heterogeneous in size, industry and product, that rationality cannot be assumed at the level of aggregate market behavior even if it holds for individual corporations (Forni & Lippi (1997,1999)), and that these agents' interactions through market rules (which are non-linear by definition) will determine how the market evolves. While our research problems have been picked with a measure of simplicity in mind, we intend to build a framework that would be robust to the introduction of more complex features and can be adapted in future for examining other markets or economic systems.

In utilizing agent-based models, we find it useful to adhere to the counsel of Mankiw (2006), who speaking on constructive modeling practices advised that macroeconomists behave as engineers in trying to solve practical problems rather than as scientists who approach modeling through upfront abstractions only to find them at odds with real-world scenarios.

This chapter is composed of two sections: A brief review of Agent-based modeling, and a detailed description of our research design.

## 4.1    Agent-Based Modeling- A Brief Explication

Agent based modeling is a fairly young research paradigm or technique for modeling complex phenomenon from the perspective that a system is an ecology of heterogeneous agents that are constantly interacting and changing the structure of that system. Miller and Page (2007) described it as "a computational simulation paradigm composed of autonomous entities that interact with each other and their environment" (p.91). Farmer and Foley (2009) more recently described it as, "… a computerized simulation of a number of decision-makers (agents) and institutions which interact through prescribed rules" (p.685). Both of these definitions emphasize

the computational nature of agent-based modeling and the importance of interaction among agents and the institutional environment–these are two features of Agent-based modeling that form its basis and run across all its variations.

ABMs have been around for quite a while, although their adoption into the social sciences is relatively recent. According to Mitchell (2009), the first ABM was created by mathematician John Von Neumann in the form of his famous self-replicating machines; thus the notions underlying agent-based modeling were developed as a relatively simple concept in the late 1940s, and did not become widespread until the early 1990's. Subsequent to the Von Neumann machine which was built on paper and is now called cellular automata, John Conway is credited with creating the evolutionary "Game of Life" which operated by tremendously simple rules in a virtual world of a 2-dimensional checkerboard. Craig Reynolds (a computer scientist) is also often credited with creating the first contemporary ABM of a social system. He tried to model flocking behavior of birds with three simple rules and the absence of a group leader in a virtual world, and succeeded in demonstrating that those three rules[28] were sufficient for the emergence of flocking behavior (Sipper, 1995). These three early works in the approach's development each show how complex behavior could and does emerge from very simple rules of interaction.

As a separate development, during the 1980s, academicians consisting mainly of social scientists, mathematicians, organizational theorists and computer scientists developed a new field called Computational and Mathematical Organization Theory (CMOT) which grew with diverse contributions from various fields concerned with how organizations function, but suffered from a lack of appropriate methodologies for its exploration. Through the evolution of computing technology, capacity and accessibility, collective design of open-source software such as

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[28] The three rules as specified by Craig Reynolds were:
- Avoid crowding neighbors
- Steer towards average heading of neighbors
- Steer towards average position of neighbors.

SWARM (around 1995) and Repast (in the early 2000s) by agent-based software developers was made possible, and has proven to be useful in pursuing some of the theoretical frameworks developed over time within CMOT. The agent-based modelling platforms were themselves developed by scientists who had taken an interest in complexity science, and had an interest in exploring phenomenon such as chaos and emergence in dynamical systems which had been topics of primary interest to physicists such as Doyne Farmer (see Farmer (1982) for an early example) for the past three decades.

However, agent based modeling has found acceptance beyond CMOT. Today, it is increasingly adopted in areas as diverse as sociology, economics, and political science (Samuelson, 2000; Bonabeau, 2002). Deploying agent based modeling in social science problems seems reasonable, given the inherent complexity of those problems, and the plethora of evolving variables that interactions within the area involve. According to Bonabeau (2002), agent-based modeling is likely to prove useful in a business context, if the phenomenon being examined involves flows, markets, organizations, or diffusion problems (p.7281). Bonabeau (2002), also outlined four major circumstances in which agent based modeling could be helpful in exploring a research problem: when non-linear relationships are likely to exist; when agents are deemed heterogeneous in their behavior and interactions; when averages are not reliable in describing a system; and when individual agents in the system exhibit behavior such as memory, learning and adaptation. Since market participants in the real world have been observed to interact through series of conditional rules and threshold conditions rather than by optimizing sets of linear differential equations (Kurz-Milche & Gigerenzer, 2007), and agents in the carbon market are heterogeneous in their emissions-sizes and market share (as we have previously discussed), averages of variables such as demand and supply would be meaningless in describing the system or estimating prices within it. Also, evidence of variable lengths of memory (which we expect even by intuition) has been found in several markets (Timmermann, 1993; LeBaron, 1995) and this feature is responsible for the ability of agents to learn and adapt- or at least to make an effort

towards learning. Therefore, based on Bonabeau's yardstick, agent based modeling appears well suited to an exploration of the Alberta carbon market in particular, and real markets in general.

Relatively recent explorations of market behavior that have been conducted using agent-based models straddle the fields of economics, finance and organizational behavior, and frequently employ contemporary insights from psychology and behavioral economics. Although economic market applications date far earlier, the earliest financial market application appears to be the simulations by Cohen et al. (1983) in which the authors tried to examine the effect of agents exhibiting random behavior on diverse market structures. Subsequently Frankel and Froot (1988), and De Grauwe, Dewachter and Embrechts (1993) created separate markets to investigate behavior within foreign exchange markets in an attempt to tease out potentially destabilizing strategies by momentum traders.

Among agent-based markets, the research styles range from purely analytic to heavily computational (LeBaron, 1995). Analytic studies such as Kelley (1956) and Friedman (1953) presented arguments which emphasized the role of agent heterogeneity in strategies and ultimate survival within an economic environment. Figlewski (1978) examined heterogeneity within the context of wealth dynamics and specifically considered how wealth dynamics affects the convergence of a market to efficiency. More recently, Bossaerts (1994) discovered that the speed of the learning process of different agents can have significant effects on the stationarity of financial time series data. All these demonstrate diverse aspects of the role that heterogeneity may play in market outcomes.

Computational models have witnessed an upsurge in numbers and variety in recent times. Drawing on recent developments in artificial intelligence and computing science, modern approaches such as genetic algorithms (GA), classifiers, and neural networks have been applied to economic and financial problems in addition to more traditional methods such as least squares learning. LeBaron (1995) advocates that the main prerequisite to determining the appropriate computational technique for a given study is having precise knowledge of: "what domain the

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agents knowledge lies in; what types of equilibria lie in that domain; and how agents move in this domain by updating beliefs" (p. 2).

Lettau (1993), Arifovic (1996), and Routledge (1994), employ the use of well-defined simple economic models that focus on learning as a tool to explore both stability and evolution of markets within genetic algorithmic frameworks. These frameworks are generally less open in structure relative to neural networks such as that used by Beltratti and Margarita (1992), and classifier based systems used by Marengo and Tordjman (1995). In generally, these studies found scenarios in which the markets do not settle down to equilibrium for long due to agent heterogeneity in terms of risk-attitude, information quality and accessibility, network-types and memory. Perhaps the most extensive agent-based market simulation to date, the Santa Fe Stock Market attempts to fuse a well-defined market trading mechanism structure with an inductive-learning oriented classifier based system (Arthur, LeBaron, Palmer, & Tayler, 1997).

Mostly, the studies discussed above belong to a generation of agent-based models in which the goal was to generate markets that do not settle down to equilibrium, and thereby grow some of the stylized facts of actual imperfect markets. Efforts were made to simulate models in which parameters were toggled within certain levels to see what combination of parameters and parameter-settings gave rise to those features. A cursory observation of these markets reveals that they were not calibrated with empirical data mostly, because their purpose was primarily to enable some understanding of how markets work in a general context and to demonstrate that complex phenomena could emerge from very simple individual behavior. Thus, although they have been useful in understanding some aspects of complexity in markets, they have not been sufficiently grounded in empirical data to afford any prescriptive or predictive value. Our use of agent based modeling differs from many of the models discussed so far in the sense that we intend to answer tangible policy questions that are specific to an identified market, and consequently there is the need to calibrate our models with data from that market. Also, while we

do not intend to build a predictive model in this current effort, we aspire to achieve some prescriptive insight by calibrating our model with some empirical data.

In recent years there have been a growing number of efforts of a similar spirit and purpose as ours, and conveniently many of these have occurred within energy and emissions markets in Europe and North America. A number of these are very interesting in the policy and design issues they tackle, and we shall discuss some details of the more influential of these next.

A large mass of agent-based modeling literature concerned with commodity markets has focused on wholesale electricity markets, and so we select only a handful that we find most useful for the purpose of this study to discuss. The popularity of agent based modeling for prosecuting electricity market dynamics may have been due to the complex nature of those markets amidst their transitions at the time (early 2000s) from centrally regulated systems to less-understood decentralized markets. The complex interactions among electricity wholesale market players are akin to the interactions studied in Game Theory (Picker, 1997), but are far too complex to be modeled by standard game-theoretic techniques due to the diversity among agents, the ability of agents to learn and adapt over time, the technical nature of the traded commodity (for which demand and supply have to be balance in real time), the oligopolistic structure of these markets, and the multiple linkages of individual electricity markets with other markets (Weidlich & Veit, 2008). Also, due to the nascent nature of the market and the consequent lack of historical data, agent-based simulations were approached by electricity-market researchers as a promising resource in scenario analysis and regulatory policy-making for that sector. With some qualifications regarding the nature of commodities involved, insights from electricity market agent-based experiments are likely to be useful in the development of carbon-market models, with the added advantage that in a few instances, such models have coupled the electricity market with a carbon market in an effort to investigate inter-market linkages (see Genoese, Sensfuß, Möst, & Rentz, 2007 for example).

Some of the earliest attempts to simulate electricity markets were made by Richter and Scheble (1998), who tried to predict the relative profitability of agents' bidding behaviors in a double-auction uniform-pricing system by using genetic algorithms. In their model, agents representing electricity generators had to make three choices during each step in the simulation: they each had to decide on how much to sell, how to predict the effective market price range in the immediate future, and at what price to sell. Agents were set up to make these choices based on varying initial genetic preferences, risk attitudes, and sophistication in prediction techniques, and upgrade their price forecast based on their perceived performance in the previous period. A market maker matches demand and supply bids in pairs and established the average of the pair as a competitive equilibrium price. Lane, Kroujiline, Petrov, and Sheblé (2000) improved upon this model by allowing electricity suppliers, who constituted the demand side, to have price-sensitive demand curves and also evolve trading strategies rather than simply being price-takers as in the Richter and Sheble (1998) model. Due to the simplistic formulation of all these early models, while they provided significant analytical insights, they were not particularly successful in capturing the empirical features of actual electricity markets.

Some pioneering work was also done by Bower and Bunn (2000, 2001), who attempted a comparative evaluation of alternative market mechanisms, such as uniform versus discriminatory bidding[29] and daily versus hourly bidding, in the electricity market of England and Wales, by building a market populated by agents that were endowed with "immediate-past" memory and reinforcement learning capabilities. They modeled the aggregate demand curve as a relatively inelastic and static curve to reflect its limited price sensitivity in actual electricity markets[30]. They also implemented a bidding system in which plants submitted bids proportional to their size, thus

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[29] Their research problem was inspired by the change from a uniform price auction to a discriminatory one that was being proposed by the UK government at the time.
[30] Visudhiphan and Ilic (1999) had previously examined the effect of price elasticity of demand in a simple analytical electricity market, and showed that lower market prices evolved from a market in which demand was price sensitive than that in which demand was inflexible. Assumptions regarding price elasticity of demand reflect the degree of market power granted to the supply side, and is an important consideration in incorporating realism into model design.

endowing large firms with more information than smaller firms under discriminatory pricing, as could be expected in reality. Consequently, they found that smaller firms performed better in uniform-price dispensations than they did under discriminatory pricing. In addition, they found that simulations with hourly bids coupled with discriminatory pricing resulted in higher market clearing prices, while daily bids under uniform pricing mechanisms yielded the lowest market clearing prices. They also observed an inverse relationship between capacity utilization and bid prices with prices falling to the level of marginal cost at total utilization levels–findings which were validated by their coherence with theoretical expectations. In Bower and Bunn (2001), the same basic model was used to explore the effect of large utility mergers on the price of electricity in the German electricity sector, and revealed a huge impact that tripled during peak seasons, while Visudhiphan and Ilic (2001) implemented a similar model in examining the impact of learning by electricity generators on strategic bidding.

Cau (2003) was interested in exploring questions regarding collusive behavior in the Australian wholesale electricity market. He developed a genetic algorithmic model in which the market price was determined by cost minimising market maker, and assumed an inelastic aggregate demand curve with equal chances of high or low demand. He identified and implemented two bidding structures namely piece-wise bidding and stepwise bidding. Agents start a bidding process by assigning bid quantities to a given price schedule, and applying linear interpolation to derive a continuous demand curve in the piece-wise case while leaving them at discrete points in the stepwise case. Agents attempt to maximise their individual gains by forecasting likely demand in the next period based on the past level of market demand and the previous spot price. Since demand can only either be high or low (inelastic otherwise), the model reduces price possibilities to a simple four, and agents attempt to evolve strategies for their bids based on how well their strategy performed in the previous round relative to other agents performance. Below-average strategies go extinct, while superior performing strategies tend to be adopted through Cau (2003)'s implementation of crossover and mutation features. The author

found that inelastic demand coupled with high overall demand increased the likelihood of tacit collusion within the model, while the inclusion of an increasing number of agents makes it difficult for agents to collude tacitly for long in most runs of the simulation.

Bin, Maosong, and Xianya (2004) and Mao-song (2004) both attempted to evaluate the performance of uniform and discriminatory pricing mechanisms examined by Bower and Bunn (2000), in comparison with a third method called Electricity Value Equivalent (EVE). While their findings appear very interesting, there was a lack of clarity about the details of both models particularly with regards to the implementation of features from the Chinese wholesale electricity market. Mao-song reports finding that relative to the other two methods the EVE increased market efficiency, allowed a higher volume of trading and induced the demand side to bid according to their true operational costs, while Bin et al. (2004) conclude that firms in the call market were less able to take advantage of market power under the EVE than they did within the traditional two.

Veit, Weidlich, Yao, and Oren (2006) attempted to explore the dynamics between a spot market modeled to resemble the German electricity market, and a hypothetical forward contracts market. Their individual agents set profit-maximising bids on both markets separately and try to learn to maximise their total profit from both markets using a modified Erev and Roth (1998) reinforcement learning algorithm with proportional action selection. They model aggregate demand as being price-responsive but linear and included a market maker each for both spot and forward markets. They concluded that trading in the forward market leads to more competition in the oligopolistic spot market and thus lowers prices in the spot market.

In exploring the pre-1999 UK electricity market, Bagnall and Smith (2005) applied a Learning Classifier System (LCS) that combines genetic algorithms with reinforcement learning. They define 21 agents (electricity generators) which differ primarily based on their electricity-generation source, with agents using the same source sharing similarities in their cost levels. Agents attempt to avoid losses and maximise profits by applying two separate LCS to improve

their performance in both respects. Each LCS includes a process of performance estimation, a decision rule on whether to proceed with the strategic status quo, a process for refining parametric settings based on feedbacks from the market, a process for generating new improved rules. Market information concerning aggregate demand and effective prices are announced to all agents at the end of that round, by a market maker, in addition to a forecast announcement of capacity constrained demand every 30 minutes during a round. The authors were interested in seeing if such a dynamic endogenous-rule-generating system could evolve actual market behavior, if the choice of market pricing mechanism implemented (they implemented both uniform-price and discriminatory pricing mechanisms) had any effect on agents' bidding practices, and if agents could learn at some point to cooperate. They find that agent behaviors resulting from their simulations are consistent with real world strategies employed by electricity generators in each of the source-classifications, the total cost within the market is higher with uniform pricing even though they bid higher under the discriminatory pricing mechanism, while cooperation rarely occurs in several runs of the model. The inability to generate cooperative action in the model may however have been due either to the nature of the LCS used which emphasizes individual strategic improvements, or a conceptual flaw in the way cooperation was defined (as two or more generators making the same high bid) within the model. Relative to other models that employed an LCS approach (such as Bunn and Oliveira (2001)), Bagnall and smith (2005)'s LCS was more complex, but shows no specific obvious gains over those models due to the added complexity. However, the model as a whole embodied laudable realism in showcasing some of the fine details of the dated UK electricity market.

In addition to the types of models discussed above, some large scale simulations of national electricity markets in the US have been developed by researchers backed with government financial and data resources. Two notable published examples of these efforts are EMCAS described by Conzelmann, Boyd, Koritarov, and Veselka (2005) and N-ABLE described by Ehlen and Scholand (2005). Both models are used to support questions of choice among

market designs from a regulatory perspective to restrict inefficiencies such as the prevalence of market power or to test for transmission grid reliability in the system. As such they are very detailed and use a mass of data from actual databases of the regions of interest such as differentiated data load schedules, actual cost schedules of the power plants and include physical constraints such as actual locational constraints within the industry.

In EMCAS, the researchers probed the possible effects of changes in the price setting rules and power plant outages on prices within the electricity market, over hours and running into decades. Thus they hoped to unveil short term physically-constrained, short term physically and economically constrained and long term economically constrained agent behavior in the evolving market. EMCAS agents are very many, with each being very complex and acting on a large number of highly specific rules that are based on genetic algorithmic programming. These agents are differentiated in terms of the types of generation facilities that they own, the location of their resources, the uniqueness of bidding strategies they employ. Agents try to exploit the physical limitations and the market rules of the power system by selling in various markets and fine-tuning their bidding strategies towards optimising their utility within the markets. Agents also rely on long memory and decide on strategies based on historical success and failure rates of those strategies under varying market conditions, while also being led by their risk tolerance level. Among other things, they discovered that discriminatory pricing mechanisms engender more stable and lower prices which entails good performance for the demand side but may imply inferior performance when viewed from the supply side since it may drive out suppliers and cause a less competitive market on the long-run.

Some efforts have also been made by agent based researchers to understand the relationship between electricity markets, which tend to be heavy emission culprits, and carbon markets. Some prominent models which have been adapted by other authors include efforts by Genoese et al. (2007), Wang, Koritarov, and Kim (2009), and Chappin, Dijkema, and De Vries (2009).

Genoese et al. (2007) were curious about the increase in wholesale electricity prices from about 10 euros to 30 euros, on the heels of the implementation of the EU ETS in 2005. They examined the integration of daily emission allowance prices into the bidding process by power plants in the German carbon market, and how that fed into wholesale electricity prices. Their main aim was to investigate how much of $CO_2$ allowance prices electricity suppliers integrated into their selling price, particularly since there was a fairly strong correlation between prices in the two related markets. The authors implemented an agent based model on the PowerACE simulation platform interlinked it with about 4 other data generating models, and incorporated 2 markets–a spot market for electricity, and a market for $CO_2$ emissions. The model they built also draws from actual data from German wholesale electricity markets such as electricity demand schedules, level of renewable electricity generation as well as actual day-to-day EU emissions allowance prices, and daily temperature figures . Agents participating in the spot market submit bids as price-volume pairs. A market operator collects and sorts all bid pairs in order of increasing price, and determines the market clearing price by the last bid necessary to satisfy demand for every hour of the day. Traded volume per hour is also determined by summing up all demand bids that can be met at the clearing price. The authors assumed that demand is inelastic in the short term in order to ensure that suppliers mopped up the total amount required by their customers, while also differentiating supply side agents by the source of energy used in generation along with the consequent differences in capacity, costs and technology. They report that their model generates spot market data and allowance prices that closely resemble actual German Data, and that at least 75% of allowance price filters into the variable costs of coal power plants while virtually all of the price is integrated into variable costs for most gas-fired power plants which also appear to bid strategically. In conclusion, they recommend the allocation of allowances to generators through auctions rather than grandfathering in order to prevent the accrual of undue windfalls to those corporations, since they invariably transfer these costs to their consumers.

Chappin, Dijkema, and De Vries (2009) conducted similar experiments using agent based modeling platforms to examine the interaction between both $CO_2$ emissions and electricity markets, with Chappin and his co-researchers adding a third market–the fuel market. Chappin et al. (2009) in particular defined the market as a large socio-technical system implemented on the Repast modeling platform, and even depict the various physical features of electricity markets that contribute to the economics of the market and contribute to create the chaotic environment that ensues. They identified 3 classes of participants in the system–agents (power producers), markets, and physical installations and compare their performance in the presence of a carbon tax alone, an emission trading system alone, and a benchmark state of no intervention. They also included features of real-world ETS such as the banking of surplus credits, and payment of penalties in the event of a shortage in the amount of $CO_2$ rights held by the agent at the end of a compliance period. Agents are empowered to make tactical decisions in the $CO_2$ market concerning how much to bid and at what price, while they also had to make strategic decisions about whether to invest in or decommission power plants based on an extrapolation of aggregate demand trends and the lifetime/lifespan attainment of the plant and its historical performance in terms of profits and losses. Agents decisions to invest in a new plant was defined as also being a function of announcements of plant commissioning and decommissioning by competitors, although the authors leave some room for uncertainty in strategic planning by making decommissioning due to unannounced losses to be unannounced. Agents that decided to invest in a new plant also had to choose the technology for the new plant (whether nuclear, coal or gas) based on their risk attitude, level of conservatism and aversion to nuclear power. They also iteratively introduced arbitrage in the demand for $CO_2$ to solve the problem of simultaneously clearing markets in such a way that total annual demand for $CO_2$ meets the emission cap, and a single annual $CO_2$ price develops. They ingeniously attempt to keep the $CO_2$ prices equivalent in both carbon trading and carbon tax cases by adopting an emissions cap calibrated with the EU

ETS Phase III design, calculating the average of the $CO_2$ prices over a 40 year span[31], and setting that as the carbon tax level. They conclude that both policy options are effective in reducing $CO_2$ emissions provided that ambitious caps are set in order to incite some upward pressure on $CO_2$ price.

Another relevant string of research that has been given some attention especially by researchers from the SPRU group at the University of Sussex is agent based modeling of personal carbon trading schemes. Kempener (2009) presents an ABM that is based on hard UK micro-level data from the 2005 - 2006 Family Expenditure Survey about household income levels, energy use, and energy prices and technology options. The author describes a compliance market for UK households in which households are allocated an amount of allowances each year based on a number of factors and have to surrender some of these for every emission-producing activity they engage in. Using the Anylogic modeling platform (a brand of agent-based modeling software), the author also specifies sets of decision rules by which households (who are either economically focussed, environmentally conscious or socially driven by nature) make 4 decisions including their consumption of holidays, investment in emission-reducing technologies, determining the price of carbon, determine the marginal cost of buying carbon credits.

In Kempener (2009)'s model, households are designed to act in response to changes in energy prices and the environmental consequences of energy consumption, with each class having 6 specific rules of behavior. There is also the inclusion of a market maker who determines the equilibrium price as the point of intersection of the amounts and prices at which individual households are willing in buying and selling credits. Households above or below the equilibrium price in each trading session, record no trades both on the demand and supply sides. An endearing attribute of the model is that it implements a sliding cap of 10% allowance reductions per year on the market, relative to the previous year's credit allocation. This feature mimics the central

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[31] We also adopt a 40 year period for our study similarly to Chappin et al. (2009). Our choice is based on the fact that this time-span is synchronous with the climate-planning horizons of most jurisdictions which have carbon reduction targets and projections up to 2050.

feature of price caps in facility compliance schemes that are currently in operation, and instills an emission reduction function in the system. The author conducted 6 experiments in all with 3 exploring the effect of household behavior on the effectiveness and efficiency of the market, and the other 3 experiments examining the effect of market scope on the efficiency and effectiveness. He reports that although absolute emissions reductions occur within the model, the market operates inefficiently (with price not reflecting the underlying abatement costs) and ineffectively (with actual emission reductions mostly being below the possible level of reduction). He concludes by asserting that agents within real markets probably respond to other stimuli besides a utilitarian mindset, and behavioral changes will be necessary in order to arrive at an efficient and effective system.

While the list of agent based models examined above is far from exhaustive, it serves mainly to indicate the themes and operational design choices made by modellers, as well as the types of issues and questions that they have been primarily concerned with. There are some similarities among these models and some "traditions" may have evolved over time. One of such is the tendency to represent the markets with a fixed price-insensitive demand (usually) or supply side. This is obviously motivated by two considerations: a quest for simplicity which this depiction allows, and a general tendency for the demand side in actual electricity markets to be at least inelastic due to the essential nature of the commodity. Another similarity is that most agent based models of electricity markets tend to be concerned with market pricing mechanisms and market power. This is because the framework actually lends itself to the exploration of those knotty problems that are intrinsically complex and most fruitfully examined without the omission of learning and adaptive capabilities of agents within actual markets. According to Weidlich and Veit (2008), one important area of enquiry into research design which has not seen much activity is bilateral trading (which we discussed in section three as an informal market pricing mechanism), which enjoys a significant share of actual trading in commodity markets.

Generally, we agree with Weidlich and Veit (2008) that the modeling technique is promising but still in an adolescent stage, and exhibits a lack standardization in terms of its calibration, validation, and reporting. Perhaps more fundamentally, agent based researchers seem to be concerned primarily with examining stability as equilibrium within the markets while neglecting the incidence of perpetually out-of-equilibrium phenomena, and the paths that lead to them. This neglect undermines their contribution to economic literature, because a major motivating factor in the application of agent based models to markets is the need to gain some understanding of chaos and cyclical trends that ensue where multiple equilibria exist, as in the real world.

## 4.2    Research Design

Our aim in this section is to describe the basic features of the model we built, and then progress to a description of the experiments to be carried out, and finally discuss some issues regarding calibration and validation of the basic model.

### 4.2.1    The basic model.
Our basic model borrows heavily from concepts earlier developed by Marengo and Tordjman (1995), LeBaron (1995), and Arthur et al. (1997) such as the classifier based system , and the concept of cellular automaton developed in large part by Wolfram (see Wolfram (2002) for a very readable exposition). It is also an attempt to adhere to Bonabeau (2002) and Mankiw (2006)'s counsel on best practices and practicality. Since our primary quest is to answer some basic questions about a specific observable market, we started by building a very simple model, including only those elements of the actual market that we consider absolutely vital to its existence. For illumination, we present this basic model by describing it from the bottom up, starting at the lowest level of economic agents through to systemic issues such as trading mechanism, and software-implementation. We also discuss those features as they

exist in the actual market and give justification for instances where our model inculcates a different characterization.

*4.2.1.1 Agents.* By definition, agents in every market can be broadly classified into two groups; buyers (the demand side) and sellers (the supply side). From the Specified Gas Emitters Regulation (Alberta Environment, 2011), we can clearly identify the buyers as the large regulated emitters who require carbon allowances for meeting annual compliance targets. In our base-model, these same regulated firms alone constitute the sellers in the market. The implication of this, which allows for a tight system in which allowances can only be generated by reductions in regulated firms, is that only EPCs are available for trade. Thus, if a corporation exceeds its emissions in a given year, in order to pay less than the CCEMF rate, some other regulated corporation must have reduced its own emissions below target and be willing to sell the excess at a price below the CCEMF.

These large emitters summed up to about 58 corporations in number (about 100 production facilities), and all qualified for the regulation cadre by emitting an excess of 100 mega-tonnes of CO2 equivalent (mtCO2e) in the year 2010 although the actual sizes of emissions in the market varied greatly. We laid the foundations of the model by setting up a virtual market in which exactly 58 emitters exist, which differ primarily in terms of their annual reduction targets and internal reduction capacity (IRC). We categorised regulated emitters into 3 cadres–Huge, large and small–based on the sizes of their emissions, and calculated initial annual reduction targets as the difference between average 2010 and 2005 emissions within each class[32]. We also implemented a 2% annual rate of increase in targets and scheduled it to apply from 2014 onwards as required by the SGER regulation in the actual market. Next we computed their respective IRCs by assuming that large Oil & Gas and Coal-using companies have a natural

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[32] See Table 4 in Appendix C for information about actual emissions by the top emitters in Alberta that exceeded the 100 $KtCO_2$ threshold in 2010–this data was extracted from an Environment Canada (2010) report.

capacity to reduce emissions every year by 1% due to process improvements accessible by their scale of operations and nature of products while non-energy companies such as chemical and fertilizer companies have a smaller capacity of 0.5%[33]. We then randomised the distribution within each class in order to allow for variability and heterogeneity among the agents, and infuse the model with more realism than would be possible if 3 homogenous groups existed.

Each agent in our model is designed to make its decisions independently, and apart from unique targets and IRCs, has to make decisions on whether to buy or to sell allowances at a point in time, or to commit to a long term investment at the beginning of each year. In arriving at these decisions, each agent has to formulate some expectation of future prices based on its outlook or worldview about the behavior of prices. An agent's outlook can either be "fundamental", "momentum" or "contrarian" at a point in time, and in order not to bias our agents unnecessarily, we randomly assigned outlook to all agents in the model. Thus any agent–irrespective of its size– has an equal chance of being born with any of the three outlooks informing price expectation, and we will expect roughly equal proportions of agent holding the 3 alternative outlooks.

We define a fundamentalist expectation as one in which an agent believes that there is a tendency for prices to always return to a fundamental value. We assume this fundamental value to be the average cost of abatement that is prevalent in the market at a point in time. We use a simple linear function to depict this expectation thus:

$$P_e = P_{t-1} + \{\alpha_f * (ACA - P_{t-1})\} \tag{1}$$

Where:

$P_e$ = Expected price in current period

$P_{t-1}$ = Price in previous period

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[33] See Table 5 in Appendix C for details regarding our calculations. These calculations are derived from Environment Canada (2010)'s Reported Facility Greenhouse Gas Data.

$\alpha_f$ = coefficient of change ; this parameter symbolizes the magnitude of anticipated change

ACA = Average Cost of Abatement

Fundamental expectation implies a conservative approach to price movement based on a perceived intrinsic value. Fundamental agents in our model differ in the value of $\alpha$–that is they have various notions of how big the size of that reversion towards a fundamental value will be. We assumed a random value from 0 to 1 for $\alpha$.

We define a momentum outlook as one in which an agent believes that prices tend to keep moving in the same direction as they did in the previous time period. Therefore if there was a price increase in the previous period, a momentum trader assumes that the direction of this change will continue in the current period. We describe a momentum emitter's price expectation thus:

$$P_e = P_{t-1} + \{\alpha_m * (P_{t-1} – P_{t-2})\} \qquad (2)$$

Where:

$P_{t-2}$ = Price in the next-to-last period

And all other parameters retain the same meaning as in (1) above.

Momentum expectation implies a tendency of an agent to perpetuate a trend in prices and exaggerate price movements. In general, these agents move in the direction to which the market seems to be moving, and tend to push it further that way. This is a realistic feature of many real-world market agents who tend go with the majority perhaps due to a lack of technical or fundamental information about prices within the market. Similar to fundamentalists, we assign random $\alpha_m$ values (varying between 0 and 2) to emitters to introduce some heterogeneity among them regarding their expectations of how much the magnitude of change will be. Emitters with

αm values below 1 expect the change to be less in magnitude than in the previous period, while those with above-1 values anticipate a larger than previous price change.

We define Contrarian expectation as an expectation that prices will change in an opposite direction in the current period relative to the change experienced in the period before that. Contrarians expect that if a price increased in the last period, it will decrease in the current one, and if it decreased in the last period, it will increase in the current one. Arithmetically, we depict the expectation formulated by emitters with this outlook thus:

$$P_e = P_{t-1} + \{\alpha_c * (P_{t-1} - P_{t-2})\} \hspace{3cm} (3)$$

Where all parameters retain their meanings as in (1) and (2), but the value of αc ranges between -2 and 0 to capture the opposite nature of the contrarians expectations. We randomly assign values to emitters, with fraction-values implying conservative expectations in terms of change magnitude, and values equal to or above 1 implying a change equal to or higher than the change in the preceding period.

Based on the price-expectation models afforded them by their respective outlooks and a series of behavioral rules that they are endowed with from their creation, our agents (emitters) are able to decide on whether or not to make a long run investment at the beginning of every year and how much to invest, and to determine if in any period they should place a demand or offer supply to the market. A huge firm's long run investment decision for instance, is typically predicated on a simple rule specified thus:

If:

- Period is after 2020

- And level of investments = 0

- And credits available for supply < 20% of annual target

- And arithmetic mean of market-prices over the past year > ACA

- And CCEMF > Average cost of abatement * Transaction cost

- And a randomly picked positive fraction > the assumed propensity to invest

*Then*:

- Make investments that will yield M * 50 MtCO2 worth of allowances

- And once time = Time of investment + 10 years

    - Transfer M * 50 MtCO2 into Warehouse for onward supply

    - Announce supply amount.

Where M is the same randomly assigned variable used for size distribution among classes, and is generally a positive variable distributed with a mean of 1 and standard-deviations of 0.48, 0.65, and 0.73 for huge, large and small emitters respectively. The implication here is that if a regulated firm chooses to invest in low-carbon technology or CCS for instance, that firm's investment is proportional to its size. We think this is both a reasonable and realistic assumption, and adopt very similarly specified decision rules for emitters in the other two classes.

Quite obviously, the long-run investment rules of our agents imply that they do not attempt to optimize profit, minimize cost nor maximize revenue. In order to allow for simplicity, we do not assume that emitters are optimizing agents, and neither do we use the optimization concepts of profit, cost and revenue. Instead, our agents are built on the premise that they try to satisfy a need–to meet carbon compliance requirements in the cheapest way 'they can'. This implies that they have limitations, and are neither imbued with perfect rationality, nor do they have access to perfect information about prices or moves by other agents. Rather, they have some information, and some rules (not necessarily optimal ones) upon which they make their decisions. While this greatly simplifies the model however, it also appears to be a more realistic depiction of agents in actual markets where agents have been observed by researchers such as Nagel and Greenwood (2008) to operate with bounded rationality and irrationality.

Our investment / supply side specified above also warehouses an implicit assumption: that supply is price inelastic. This is likely to be fairly true as the actual Alberta carbon market evolves because once these capital investments have been made and a low-carbon project has

matured, suppliers are likely to be hard pressed to sell the allowances to recoup their costs even at low prices particularly if there is a glut of permits. However, we describe investment as price elastic with higher levels of investment occurring when prices are high while lower levels occur when prices are low.

Emitters in our model also have to make decisions regarding demand since each emitter is given a target at the beginning of each year that must be fulfilled by the end of that year. Of course, since the penalty for default as specified in the Alberta Specified Gas Emitters Regulation 2007 (Alberta Environment, 2007) is payment of an amount equivalent to 3 times the maximum price (that is the CCEMF fee), it is safe to assume that emitters will go to great lengths not to default.  Therefore, for emitters that are unable to meet their targets through internal means, only 2 choices exist–to buy from those that offer to sell or to pay into the CCEMF as a last resort. Since CCEMF is a price cap, there is likely to be a discount by purchasing allowances. Our agents decide on whether or not to demand for a commodity based on simple algorithms, the typical form of which we specify thus:

If:

- Annual Target emission reduction > Current level of emission reduction

- And In-house supply = 0

- And Expected price < (CCEMF - $3)

Then:

- Set the difference (called Target balance) to autonomous demand

- Place a demand = autonomous demand–demand coefficient * Pe

If Supply > 0  but Supply > demand

Then:

- Move entire supply to fill demand

If Supply > 0 and Supply > demand

Then:

- Move the quantity of allowances required to fill demand from supply

- Cancel demand

- Reset supply to (Supply–Previous demand)

The algorithm described above uses sets of rules to determine the conditions under which to purchase allowances, and uses a simple linear demand function of the form:

$$Q_d = Q_0 - bP_e$$

Where:

$Q_d$ = Quantity demanded

$Q_0$ = Autonomous demand          (We set this value to equal Target-balance)

$b$ = demand-coefficient (This parameter captures the degree to which emitters are sensitive to changes in price and we assume it varies between 0 and 10)

$P_e$ = Expected price          (calculated based on each emitter's outlook)

As with their supply-side and investment rules, our agents' demand rules do not also show aspiration towards optimization of goals–they merely seek to meet the compliance target based on the little intelligence they have been endowed with through the specified rules and their basic behavioral equations. We utilize these very simple equations to operationalize both price-expectations (as earlier described) and demand behavior because while those corporations probably do not use them in real life decision making, we think that they approximate the relatively simple threshold rules that they use, while helping us to eliminate several hundred lines of threshold-rules that would have been necessary for program-implementation purposes. This is in consonance with Wolfram (2002 p. 49)'s thoughts concerning complexity in the real world–our aim is not to define many complex rules in order to generate the complex phenomenon that characterizes the real world, but to define simple rules (and equally simplistic equations) and see if they generate those complex phenomenon. Therefore, although we aim at realism, we pursue it in a convenient mix with tractability.

One unique trait of all agents in our model that we deem necessary to emphasize is the fact that they do not seek to optimize but attempt simply to satisfy their needs. While avoiding the optimization assumption allows us to more realistically model the market (No industrial firm is likely to expend several man-hours on computing profit maximising level of allowance purchase), the strategic implication of this is that it allows us to avoid explicit modeling of cost, revenue and profit functions, and thereby greatly simplify our model. It also allows us to avoid the more complex modeling of deliberate competitive behavior among agents which despite being a very important feature in reality is unlikely to add enough value to the resolution of our immediate research questions to justify the increased complexity it would add. Therefore, our agents are substantially more intelligent than the zero-intelligence agents implemented by Gode and Sunder (1993), but significantly less so than the algorithmic traders used by Arthur et al. (1997).

Another feature that we also included in our model, which we had glossed over in previous paragraphs, is memory. We endow all agents in our model with short term (last-period) memory for period-to-period their demand transactions, and longer-term (last-year/50periods) memory for annual investment decisions. While the lack of heterogeneity in memory-spans may detract from the realism of the ensuing market, we observe that heterogeneity in memory is probably less germane to our research questions than the other aspects of diversity in the market. Our model is a base model and does not also implement the very interesting concept of strategic learning for the similar reason that it is as unlikely to be useful in confronting our current problems as memory-heterogeneity. It would be interesting in future however, to explore how the inclusion of these features that are observable in actual markets can make the model useful in exploring issues concerning strategic evolution.

*4.2.1.2 Trading Mechanism.* Our model is a virtual depiction of the Alberta carbon market, and so requires a trading mechanism; a mechanism that mediates between demand and supply, and matches them to some degree in order to determine an effective market price.

Conventionally, trading mechanisms are also applied to bring the forces of demand and supply into equilibrium (for instance, the traditional open perfect market in economic theory which assumes information symmetry and an omniscient market maker), but this is a purpose for which we do not intend the mechanism in our model. In building the model we tried to void making the explicit assumption that the market approaches equilibrium or oscillates around equilibrium–in fact we made no macro-level assumption about equilibrium because we perceived this as an artificial interference with emergent behavior that naturally ensues from the interaction of rules executed by agents in our model.

Our implementation of a trading mechanism is simply aimed at clearing the market with no effort being made to bring demand and supply into equilibrium. Agent based markets mostly handle the clearing problem either; by assuming that price simply adjusts to excess demand, by constructing a market in which temporary equilibrium prices prevail or by explicitly modeling trading in a continuous form as prevalent in actual markets (LeBaron, 2001). We adopt the first approach highlighted by LeBaron, choosing to equate demand and supply at the level of the lesser between the two variables and allowing price-expectations in the market to adapt to the resulting excess demand or excess supply. Our mechanism is operationalized as an auction mechanism in which calls are made for the sale of multiple parcel of identical allowances (presumably submitted to a central auctioneer by suppliers), and prospective purchasers submit bids for the amount they require at sealed prices that the auctioneer then averages to arrive at the market price. In essence, our basic model uses a trading mechanism based on a Uniform-price auction design. We choose this approach in order to capture some realism in the actual operation of our virtual market, and avoid the unnecessary distraction that an equilibrium goal will cause.

In line with the tenets of uniform-price auction, we assume that once all bids have been collected, if demand exceeds supply, the auctioneer serves the bidders starting with the highest bids and keeps moving down the line until all units of the good have been sold, whereas if supply exceeds demand, the order with which allowances are allocated to bidders is immaterial since all

bidders will get to receive the amounts they bid for insofar as they bid above the sellers' reserve prices. We implement this trading mechanism by setting market rules typically structured thus:

If aggregate demand > aggregate supply in period t-1

- and the gap is less than 1,000 units

    Then:

    - Increase price in period t by (0.01% * Aggregate demand - Aggregate Supply)

    If gap is > 1000 units but less than 10,000 units

    - Increase price in period t by (0.02% * Aggregate demand - Aggregate Supply)

    If aggregate demand </= aggregate supply in period t-1 and gap is less than 1,000 units

    Then:

    - Reduce price in period t by (0.01% * Aggregate demand–Aggregate Supply)

    If gap is > 1,000 units but < 10,000 units

    - Reduce price in period t by (0.02% * Aggregate demand–Aggregate Supply)

Again these rules are crude, but they capture the assumed relationship between price and the pressure implied by an excess in demand or supply. We tinkered with many runs of simulations to arrive at the 0.01% and 0.2% values which generally yield reasonable price movements. Nonetheless, these values are arbitrary and constitute a strong assumption regarding the responsiveness of price to the market forces, which future studies could calibrate with real market data. Since we do not hope to make quantitative forecasts with this base model without some tighter calibration though, we adjudge this assumption to be necessary and acceptable for our purposes.

*4.2.1.3 The world.* This is the highest level of aggregation in any virtual model. Defining the world for each simulation of our model entails determining how agents are represented, determining the number of agents, determining whether or not variables have locational constraints, determining what variables agents can influence (personal variables alone or can they

influence other agents' variables and global aggregates?), determining how and whether the world itself changes or evolves due to agents interactions, and possibly specifying a series of parameters that depict a 'state' of being in the world that is of interest to the researcher as well as a time span within which the world starts and ends. The world is also defined by the choice of modeling software, and its possible interface with other analytical or computational software that may be used to augment its processes.

The world in the context of our basic model is represented by an 8 by 8 2-dimensional square grid of 64 square immovable cells (called patches) that wraps around both horizontally and vertically and can be expanded to include more cells or increase in scale. We represent the emitters in our model as cells and distribute population such that 10% of the cells represent huge emitters, 20% represent large emitters, and 70% represent small emitters. We then assign other properties to the emitters as already discussed above. We set the colors of our huge emitters to blue, our large emitters to green, and our small emitters to pink to enable easy visual identification. Furthermore, we assign a movable object (called a turtle) which has the resourcefulness of maintaining its own unique identity while also having access to the features of the cell upon which it grows, to each cell. These 'turtles' are shaped as kites and we use them primarily as activity indicators that turn red when a cell (or emitter) is making a demand call or white when a cell (or emitter) is making a supply call, but is the same color as the cell by default and so is invisible until the cell makes a call. The turtles make it possible to have a rough idea of what is going on in the market by merely looking at the world.

The world is set to ticks corresponding to trading periods, with each tick representing a period and the final tick of 2001 being the end of 40 years. Based on our observation of actual carbon markets, we suspect that carbon trading is likely to occur in Alberta with far less frequency than stock trading, and so we equate a tick with a trading session that occurs once a week, with 50 such sessions occurring within a year, and 2000 sessions or ticks constituting 40 years. Thus, our model hypothetically displays market trends up until the year 2050. However

this interpretation is not cast in stone; the assumption about trading frequency may be relaxed with very little if any foreseeable impact on the models output with minor adjustments in inputs such as time the time it takes for investments to mature.

In the world in our basic model investments made by huge emitters take 10 years to mature, those by large emitters take 6 years, while those by small emitters take 4 years to mature. We justify this implicit assumption regarding time to maturity on the reason that bigger investments probably imply larger projects which could reasonably take longer to complete.

Emitters in our world are not mobile in this basic model because the physical arrangement of the cells is not assigned a meaning. Therefore it matters little whether or not cells are neighbours. In future, we hope to assign some informational value to proximity of cells to engender more realism, and depict some level of information asymmetry. Emitters in our world also are not born and do not die. They are simply firms that are bound to participate in the market because they exceed the regulated emissions threshold in a given year, and are compelled by regulation to continue reporting their emissions even in years in which they manage to stay within their assigned emissions target. In those years however, they may participate mainly as suppliers of allowances.

*4.2.1.4 The Software and Its interface.* Our world is implemented in Netlogo 5.0.1; a software created by Uri Wilensky (1999) at Northwestern University. It is a multi-agent modeling environment that is based on a Java platform and employs object-oriented programming. We chose to use Netlogo because it is the most accessible of agent-based modeling software, allows an enormous amount of flexibility, has a comprehensive documentation vested in its user manual, code dictionary, and vibrant user community group, and has seen a lot of recent use in the agent-based modeling community. Netlogo is also very compact and has a download weight of just about 90 megabytes, making it much easier to run on a laptop, and much faster as well. It also

features a compiler which offers a host of primitives (somewhat like shortcuts) that make it easier to program than writing the code strictly in Java would be.

We considered other software- particularly Repast and Swarm- that are popular in the agent-based modeling community, but chose Netlogo for some reasons. While being a very powerful and unarguably more flexible software, Swarm lacks the kind of comprehensive library that Netlogo offers and does not have a composite repository. While both software (Netlogo and Swarm) are open source, Netlogo exercises more exclusive ownership rights in its platform development while the Swarm platform is actually developed by a multitude of users and is thus always in a constant flux of (progressive) chaotic development. Swarm also suffers from numerous bugs due to its rapid spate of development. Also, because the Netlogo has its modelling language which is built on Java and is easier to learn, it allows easier bug-fixes. Repast is tamer than Swarm, but does not enjoy as much accessibility as Netlogo. Perhaps most importantly, Netlogo is more widely used than either alternative software by agent based modellers. This makes it a more widely accessible agent-based modeling platform and language than most others, and aids easier dissemination of research done with it.

Netlogo affords the facility of visual representation of a world, as well as the option of constructing basic time-series graphs in order to allow easier observation of trends. In addition it offers tools such as 'buttons' that can be used to give instructions (such as "setup world" or "start simulation") to agents in a model, as well as 'sliders' that make it possible to adjust the global parameter-settings in a model. 'Output boxes' which show values of variables and 'Choosers' that enable toggling among states of the world can also be designed as part of a model in Netlogo.

The interface in our model displays 2 buttons, 10 sliders, 2 choosers, 3 charts, and 4 output boxes along with the centrally displayed world. The sliders and choosers serve as input devices; choosers are used to specify what experiment to run, while sliders are used to calibrate the model with the actual scenario of interest. In essence, these are the explicit assumptions of the experiment which are not hardwired into the model. This feature makes the model very flexible,

very robust and adaptable to various uses and various scenarios. The validity of output derived from the model thus depends upon the quality of parameter settings imputed by a user in terms of its coherence with reality. Next we give a brief description of elements of the interface:

*4.2.1.4.1 Buttons.* The 2 buttons on the interface are specified as follows:

"Setup" button: The setup button is used to set-up the market. This button specifies characteristics of the firms which are either huge emitters, large emitters, or small emitters.

"Go" button: Starts the simulation. It has been set to run for 2000 ticks which represents about 40 years of once-a-week carbon trading (roughly from 2012 - 2052).

*4.2.1.4.2     Sliders.* The nine sliders represent parameters and are specified thus:

Alphaf ($\alpha_f$): Sensitivity parameter for the fundamentally-minded firm which forecasts price as $P_e = P_{t-1} + \{\alpha_f * (ACA–P_{t-1})\}$ where $0 < \alpha_f < 1$. Higher values represent expectations of greater (fractional) changes in price per time and vice versa.

Alpham ($\alpha_m$): Sensitivity parameter for the momentum-minded firm which forecasts price as $P_e = P_{t-1} + \{\alpha_m * (P_{t-1}–P_{t-2})\}$ where $0 < \alpha_m < 2$. Higher values represent expectations of greater (reinforcing) changes in price per time and vice versa.

Alphac ($\alpha_c$): Sensitivity parameter for the contrarian-minded firm which forecasts price as $P_e = P_{t-1} + \{\alpha_c * (P_{t-1}–P_{t-2})\}$   where $-2 < \alpha_c < 0$. Higher values represent expectations of greater (opposite) changes in price per time and vice versa.

Demand_coefficient: is the coefficient of demand (b) in the simple linear demand equation $Q_d = Q_0 - bP_e$; where $Q_0$ is autonomous demand and $P_e$ is expected price. It represents the sensitivity of the demand by emitting firms to changes in price.

Propensity_to_invest: This is a parameter that captures the likelihood of emitting firms investing in long-term projects. It may encapsulate risk attitude (High = seeking, Low = averse), (Lack of) information about other firms' project investment decisions (High = Total Lack, Medium = some information that inhibits excessive supply, Low = A lack of motivation to invest in carbon abatement technology or projects perhaps due to risk or some other reason). At zero, it implies the virtual absence of supply in the market.

CCEMF: This is used to specify the fee level of the fund (Climate Change and Emissions Fund) into which emitters are required to pay a legislated amount (currently $15) for each excess tonne of $CO_2$ released every year that is not covered by EPCs or VERRs.

INITIAL_PRICE: This is a slider for setting a price level from which the market should start. That price is important because it may determine (at least in the short run) who gets involved in the market.

Target_multiple: This slider is useful for setting alternative scenarios where different emission-reduction targets are required by regulators. While the incumbent in Alberta is 2% (default) from 2014 onwards, the model could be used to explore the policy consequences of increasing the target. The actual target is depicted on the slider by the decimal portion of the slider amount.

Average_Cost_of_Abatement: This is the Average Cost of embarking on a long-term project such as CCS or fuel-source-substitution, per unit of Carbon equivalent abated.

*4.2.1.4.3 Choosers.* There are two choosers on the model interface specified thus:

Experiment1: The user could choose which experiment to run by clicking on the "Experiment1" chooser on the interface. The options are three:

- Run "EPConly"

- Run "VERRonly"

- Run "EPCandVERR"

Each of these represents an experiment, the details of which we discuss in the next section.

Experiment3: The user could similarly specify which experiment to run by clicking on the "Experiment3" chooser on the interface. There are two options:

- Run "Uniform-Clearing"

- Run "Discriminatory"

Each of these represents an experiment, the details of which we discuss in the next section.

The interface could also display the world in 3-dimensional space. However for our specific purposes in this study, we see no benefit from this feature besides the optical allure it gives. For clarity we utilize the 2-dimensional grid.

We advise that the model be used only in an analytical or prescriptive context rather than in a predictive one, despite the efforts we have made to calibrate it. For instance, we have not strictly calibrated the size of emissions from each firm, but have specified a random distribution based on the implied mean that we computed from 2010 Environment Canada data (Environment Canada, 2010). Similarly, in the absence of actual data we have used arbitrary values that we deem reasonable in specifying internal reduction capacities (IRCs) of these firms. Values generated would therefore only be indicative of the possible (albeit similar) trajectories that different parameter settings may have, and could aid serious policy evaluations and comparisons, but would likely be unreliable as forecasts of future volumes or prices.

**4.2.2    Experiments.** Altogether, we run 4 experiments on Netlogo. We discuss each of these experiments next, highlighting their relevance to resolving our research problems and specifying what modifications the models they involve required in addition to, or subtraction from, our basic model.

***4.2.2.1 Experiment I.*** Experiment 1 is designed to explore research question 1:

'What are the likely effects of the sources of carbon credits on volumes of trade and prices? Should the Alberta ETS include both EPCs and VERRs or just one of them? If only one source should be included, which should it be?'

We create 3 models which mirror the scenarios of interest:

*Model I (EPConly).* Regulated companies trade among themselves for Emissions Performance Credits [EPCs] only. This model is the based model that we have already described with no modifications. It represents a tight market in which only regulated emitters participate on both the demand and supply sides.

*Model II (VERRonly).* Project developers (also called offsetters) are introduced into the model as sole suppliers of VERRs and no EPCs are generated within the market (Demand/Supply Bifurcation). To operationalize this, we programed the button "VERRonly" to create new black-colored cells that represent offsetters who respond to price incentives in embarking on projects that generate offsets for emitters in our model. They make no demand because they are not themselves regulated emitters. Care should be taken in setting this model up though; the scale of the model must first be increased from an 8 by 8 torus to a 9 by 9 torus in order to add 17 potential offsetters to the market without significantly altering the population distribution of the basic model. This can be achieved by right-clicking on the world–selecting 'edit'–changing the coordinate values ('7' and '7' to '8' and '8') in the dialogue box that pops up–clicking the 'ok' button at the bottom of the box.

Apart from the introduction of offsetters and the demobilization of the supply capability of emitters, everything in this model is exactly the same as in the base model.

*Model III (EPCandVERR).* Project developers are introduced into the model to "complement" supply from Regulated emitters (EPCs and VERRs are both sold). This model differs from Model II primarily because it relaxes the assumption that emitters themselves cannot generate allowances (EPCs). In model III, both emitters and offsetters are allowed to generate allowances based on their specified rules. This model is a realistic depiction of the fledgling Alberta carbon market, in which both offsetters and emitters are allowed to generate credits by engaging in additional GHG reduction projects (for offsetters) or investing in low-carbon production technologies (for emitters).

The aim of Experiment 1 is to evaluate the three market designs on the basis of their:

1. Effectiveness in reducing net emissions by regulated emitters

2. Cumulative cost effectiveness to the market

3. Ensuing stability / instability of prices in the market

**4.2.2.2 Experiment II.** To explore research question 2; 'What effect would an increase in the number of emitters covered have on the effectiveness and efficiency of the carbon market?' we create 2 models and compare them with model I:

*Model IV (Double-size).* Model IV shall be a slight modification of Model I with the number of emitting agents increased to 128 emitters from the previous 64. In essence we intend to double the scale of the market in order to see if our model shows any traits of scale dependency. Besides the change of scale, all other attributes in the model remain exactly the same as for Model I.

*Model V (Quadruple-size).* Model V shall also be a slight modification of model I with an increase in the number of emitting agents from 64 to 256 agents. In essence, we intend to quadruple the population of model while leaving its population distribution intact. Besides the change of scale, all other attributes in the model are left exactly the same as those for Model 1.

Models IV and V are operationalized by right-clicking on the world and modifying the values of the x and y co-ordinates from (7, 7) to (15, 7) and (15, 15) respectively[34]. The main practical aim of this model is to see if the size of the market (assuming relatively similar distributions of the population) has any discernible effect on its:

1.  Effectiveness in reducing net emissions by regulated emitters

2.  Cumulative cost effectiveness

3.  Ensuing stability / instability of prices

*4.2.2.3 Experiment III.* To explore research question 3; 'How do alternative market designs compare in terms of their effectiveness at abating emissions?' we create 1 new model to describe the discriminatory pricing mechanism, and evaluate its performance in relation to the default uniform pricing mechanism of the base model:

*Model VI.* This model reflects a market that adopts a price-discriminatory auction design. To implement this model, we utilize the base model but institute rules that divert the models processes away from its default uniform-price mechanism to a separate discriminatory-price trading mechanism. The discriminatory-price mechanism that we create within the model is one in which the market clears by a procedure that ensures that each emitter pays exactly the amount that it bids, unlike the situation in a uniform-price mechanism where emitters simply pay the uniform average-price. The mechanism computes an average of the discriminatory prices paid, and reports this as the effective market price. Besides the trading mechanism, all other elements of Model I are identically replicated in Model VI.

The aim of this experiment is to decipher if there is any substantial difference in performance between a uniform-price market design and a discriminatory-price market design. Again we

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[34] See Table 6 in Appendix C for comprehensive model details.

assess performance on the basis of Effectiveness of the market in reducing net emissions, cost effectiveness, and stability in the market.

***4.2.2.4 Experiment IV.*** This experiment required no fundamental model modification, save to tweak the CCEMF slider on the Netlogo interface and examine its effect (if any) on the ensuing market.

More specifications about all models in each experiment is accessible from detailed simulation codes in Appendix B.

**4.2.3  Experimental procedure and data extraction.** We proceeded through these experiments by recording the results of 90 runs (in 3 groups of 30) for each of the models that a particular experiment involves. Typically each of these models was run without changing any of the parameters represented by sliders during a particular experiment so as to ensure that the effect seen (if any) is actually attributable to the innate feature of interest among the models. We recorded 30 observations of 3 of the macro-level variables (that are shown in output boxes on our model interface), namely: Trade volume (TV), Average cost (AC) and the Standard deviation of Market price (StdDev).

Trade volume was chosen as an evaluation criterion to reflect how much volume each design yielded and whether any perceived difference is consistent or significant. It was calculated by summing up the quantities of allowances that are traded over each 2000-tick period. Algebraically, it is specified as:

$$TV \quad = \quad \sum TV_t \quad = \quad \sum Min \ \{Ad, As\}_t$$

Where:

$TV_t$ = Total volume traded in a period t

Ad = Aggregate demand

As = Aggregate supply

And t = 1, 2 … 2000

Average cost was chosen to allow us to evaluate models based on their cost effectiveness for the market. The calculation of average cost was a little more involved, but is nonetheless expressible using basic algebra:

$$AC= (\sum[TV * P]_t + \sum[TV_i * ACA * 1.2]_t + \sum[CC * CCEMF]_t )/ (\sum TV_t + \sum TV_{it} + \sum CCEMF_t)$$

Where:

[TV * P] = value of trade in a period; generated by multiplying quantity with price

$TV_i$ = Total volume of mature investments used for in-house reduction of compliance

targets

ACA = Average Cost of Abatement

1.2 = an assumed 20% of ACA constituted by transactions costs incurred by investing in

a carbon abatement technology

CC = Volume of CCEMF contributions in a year

And CCEMF = Price of CCEMF contributions in a year; this is a constant amount adjusted

by the CCEMF slider on the model interface

In addition to these 2 variables, we also used data generated for Standard Deviation (StdDev) in price to evaluate the level of price volatility that is generated in each model (since each represents a unique feature of market design that we intended to test). We compared these standard deviations among groups to see if any significant differences exist.

To ensure reliability, we avoided the seeding resource available in Netlogo, which allows a modeller to record a set of random numbers used in a specific run of a model and access this same set for future runs, so as to ensure the same results. Since we want to be confident that our findings are not ascribable to randomness, we chose instead to run our models 90 times each for

relevant experiments, divide these 90 consecutive runs into 3 sample-groups of thirty runs each and compare the means among these sample-groups of the same model to ensure that they are not significantly different. This approach is similar to a within-subjects experimental design used in human experiments with the distinction that our subjects here are sample-means of aggregate variables rather than characteristics of individuals' exposed to a treatment.

After establishing the equivalence of in-model sample groups, we progressed to compare means across relevant models of each experiment. So for instance, in Experiment I, we compared the means of trade volume, market price, and average cost among the 3 models (EPConly, VERRonly, and EPCandVERR) using SPSS to determine whether those means significantly differ from one another at a 99.9% level of confidence[35]. We choose this highly selective level of significance due to our large sample size with which we are assured that most of the stochastic variations must have been eliminated over the 30 runs for each in-model group.

**4.2.4    Calibration and validation.** LeBaron (2001) suggested that agent based models should be validated by ensuring a calibration of parameters with certain benchmark cases which converge to a well-defined homogenous-agent equilibrium. We adopt this suggestion and go a step further in calibrating even these benchmark cases with observable qualitative data and theoretical expectations.

After checking to ensure that the model is generally well-behaved and mostly obeys the theoretical laws of demand and supply, we started our calibration by fitting all parameters (designated as sliders) to current values observable in the actual Alberta carbon market.

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[35] Conversely, we adopt a 90% confidence level in testing our in-model groups for differences in a bid to mirror the same selectivity by allowing more power to reject the null hypothesis that groups within each model are not significantly different if they are truly not. Our experimental design and agent based platform affords us this luxury of stringency because of the near-absolute control we have over extraneous or random factors that may have moderated or mediated results in a human experiment or survey for instance. We also impose the 90% confidence interval in order to reduce the likelihood of making Type II errors.

Specifically, we set the CCEMF fee to \$15; Initial Price to \$ 7[36]; Target multiple–specified as the SGER post-2014 reduction rate–to 2%; and Average annual growth rate (of the economy) to 3% (Alberta Finance, 2012). The Average abatement cost (ACA) that we used was \$ 5 which seemed reasonable given that most of the schemes currently in operation are tillage schemes that have quite low costs, and exact values for the ACA were not readily available.

Having set these parameters to prevailing levels, we ran several simulations on the VERRonly-discriminatory-pricing model (which roughly approximates the current market scenario) to determine reasonable levels for the five sensitivity parameter sliders–alphaf, alpham, alphac, demand-coefficient, propensity to invest. We obtained the most reasonable range of values at settings of 0.6, 0.5, 0.5, 3, and 0.25 for the parameters respectively. At these settings, we had results varying between 17,000 $KtCO_2e$ and 28,000 $KtCO_2e$ for cumulative supply, market prices varying between \$6 and \$13, and total CCEMF contributions of about 245 Mt for a simulation that ran for only 400 ticks (roughly equivalent to 8years). These results appear similar to recent data from the offset market particularly the cumulative supply of registered offsets reported by the regulators in  August 2012, of about 24,566 $ktCO_2$ for abatement activities engaged in between 2007 and 2011 (EOR, 2012). Also, the simulated price range appears reasonable, although the simulated CCEMF contribution level seems quite overstated. This might be because of the caveat to the SGER regulation that exempts new facilities from compliance until 2014, or possible non-compliance by corporations due to current loopholes in monitoring frameworks.

The huge variance in the range generated from our simulations[37] however reinforces our conviction that the model should not be used predictively, especially for shorter terms during

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[36] This is reported by Alberta Agric. (2012) as being within the range of allowance prices since the market's inception.

[37] The variance is mostly attributable to the random distribution of the population in our Netlogo code which implies some variability among runs. However, we noticed that these variabilities among successive runs of the same model tend to reduce after 1,500 ticks when the model-runs seem to converge to relatively similar outputs.

which the market has not settled. Even for comparative analysis, the model is unlikely to perform reliably in the short run because the rules it embodies are specified with long run goals in mind. Therefore we advise a minimum simulation length of 2000 periods.

The current assumed ACA of $5 is likely to become unrealistic in the long run even though it is currently prevalent. Generated mainly from tillage and other farming practices, it is unlikely to be sufficient in meeting with the medium to long-term abatement needs of the region's industries. CCS projects and substitutions of high-carbon processes with low-carbon ones in extractive and power generating industries are expected to provide the bulk of VERRs and EPCs within the market in a few years, and according to the IMC Report (2008), these are unlikely to be accessible below a $50 minimum cost per $tCO_2$, and could be as expensive as $300 per $tCO_2$ for much larger projects. Therefore for our simulations, we set the average cost of abatement to $75 which appears to be a reasonable incentive for the level of supply that the regulators in Alberta hope to generate. Consequently, we set a default CCEMF level of $110 per $tCO_2$ after running the model and observing (predictably) that no trade occurred with the maximum price being set below the cost price and even at a price of $90 (under the EPCandVERR model[38]). We also adjust the default rate of economic growth to 2.8% per annum which adheres better with the longer term profile of Alberta's economic trajectory (Alberta Finance, 2012).

Any claim to validity in this study, with regards to the research questions already outlined, relies primarily on the efforts made to calibrate the model. The fact also, that the experiments are highly controlled with little likelihood of external interference, while models were deliberately ascribed specific unique and explicit characteristics and are all exactly the same otherwise, gives some confidence that differences that may ensue among models emanated from manipulations to the base model and not due to chance. Our tests of differences among sample means within the same model-group also give confidence that these findings (where they

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[38] For most of our simulations, we use this model specification because it appears most similar to the design in use by the Government of Alberta. Table 6 in Appendix C presents the parameter, world and model specifications used in each of the experiments.

consistently show a difference among the models but none within groups of the same model) are not spurious but statistically significant.

While selection bias is unlikely given the virtual laboratory setting of our study and the expansive sample sizes adopted, we took cognizance of the danger that intervention bias (as described by Hartman, Forsen, Wallace, and Neely (2002)) might present as a threat to validity in this study, and took some precautions from the onset by compartmentalizing our codes in Netlogo in order to ensure that only the specified features were modified. Also to address experimenters' bias, we evaded the upfront formulation of hypothesis concerning our research questions, preferring to see the results produced by the model and analyse this objectively. During the model building phase, some runs produced inconsistent results which helped us to identify logical lapses in the model and address them. Others however, produced results that were consistent but unexpected. We did not seek to modify a model due to these, because we realised that analysis of such "surprises" might reveal relationships that are generally overlooked.

## Chapter 5: Simulation Results

### 5.1      Preliminary Observations

By simple visual observation of the model world and graphs during simulations, some trend patterns appear to clearly differ from one another. An example in Experiment 1 is the obvious difference between trends emanating from the EPConly market, and the VERRonly market. However, the extent of semblance among trends in other markets such as that between the EPConly market and the joint EPC and VERR market are not quite as clear. Thus, we use basic statistical tests of difference in means (formally called the one-way ANOVA) to illuminate on whether these designs differ significantly or not.

From the first experiment, we observed that with sample groups of up to 30 means, within-model group differences are very insignificant (generally $p > 0.10$), and therefore we economize time and effort for runs in subsequent experiments by limiting these to 30 runs for a single group per model of interest, and directly comparing the means among those models through ANOVA.

In general, the models appear to generate time-series that exhibit lengthy periods of calm immediately followed by sharp crashes or bubbles, not very different from those observable in financial market trends between 1990 and 2011. This is one of the stylized facts in economics that traditional macro-economic models have been inadequate in explaining or developing, and having it occur naturally within our models might be indicative of the models' higher level of realism relative to conventional models.

Further, we observe that the Wiener process scaling relation does not hold in the volatility of prices generated by the models. For example, given that the Weiner process extrapolation of annual volatility is expressible as:

$$\text{StdDev}_{40\text{yrs}} = \text{StdDev}_A - 40_{\text{yrs}}^{1/2} \qquad , \qquad \text{(which reflects a random walk)}$$

From a typical simulation of our basic model we obtain:

Annual volatility (volatility over 50 ticks) = $9.72

And Computed volatility over 40 years (2000 ticks) = $24.67

Substituting this into the Levy stability exponent ($StdDev_{40yrs}$= $StdDev_A$–$40_{yrs}^{1/\alpha}$) gives:

$24.67 = $9.72 * $40^{(1/\alpha)}$

Thus $\alpha$ = 3.96, which is nearly double the random walk expectation for $\alpha$.

Also, if we use the first year volatility from our simulation, and set $\alpha$ = 2 to estimate the efficient market scaling for volatility, we obtain an expected 40year volatility of $61.47–An overestimation of the generated volatility by a factor of about 250% (61.47/24.67). The magnitude of this overestimation also indicates that the market deviates substantially from efficiency, and that the level of volatility in the market would be overestimated by volatility scaling based on the assumption of a Gaussian random walk.

## 5.2    Experimental Results

Experiment I: Experiment I entailed the comparison of markets within which EPCs alone, or VERRs alone, or both EPCs and VERRs (Joint-source) existed. The purpose of this experiment was to know if there were any significant differences among the types of markets these sources of allowances defined, and what (dis)advantages any of them presented over the others if any.

Comparison of the trade-volume means of the three groups reveals that the highest volume was traded in the VERRonly market (TV5 = 13,500$MtCO_2$) which was more than double the average amount sold in the EPConly market (TV2 = 5,816$MtCO_2$) and the EPCandVERR market (TV8 = 4,049$MtCO_2$). Our statistical analysis of the sample means generated from the three distinct models showed that trade volumes were not significantly different between the EPConly and joint-source (EPCandVERR) models at a 10% level of significance, while they were highly-significantly different between the EPConly and VERRonly markets, and the EPCandVERR and VERRonly markets as the sample means suggest. All three markets were also found to be highly-significantly different in terms of their average costs with the average cost

mean for the joint market being the lowest (at AC8 = \$110.248), followed by the EPConly model (at AC1 = \$114.63) and the VERRonly model (at AC6 = \$117.63). The level of volatility (as indicated by the StdDev measure) reflected by the sample means of each of the models indicated very low volatility with standard deviation in market prices being about \$8 in the VERR model[39], while the EPConly and EPCandVERR models yielded standard deviations of about \$23 and \$28 respectively.

Experiment II: is aimed at examining the existence or absence of scale effects in the Alberta carbon market, and to explore this, we examine 3 models in which size is increased by a factor of 2. The smallest model is simply the third group from experiment I which features a joint EPC and VERR design and a uniform-pricing market design, with its scale reduced to 8 x 8 from 9 x 9. We reuse this model because of its similarity with the Alberta design currently in force, and the fact that it was one of those validated by the in-model test prior to Experiment I. The small-scale model consists of 64 cells, the medium-scale model consists of 128 cells, and the large-scale model consists of 256 cells.

We found that the mean of trade volumes in the medium scale model (at TV = 8,024$MtCO_2$) was a little more than twice that of the small scale model (at TV = 3,476$MtCO_2$), but a little less than a third of the trade volume average in the large-scale model (at TV = 24,834$MtCO_2$). These differences were confirmed to be highly significant at the 99.9% confidence level. Average cost sample means were also highly significantly different at the same level of confidence with means of approximately \$111, \$107 and \$98 for small-scale, medium-scale and large-scale models respectively. The sample means of the StdDevs for medium (at SD = \$28.9)and large scale (SD = \$36), and small ( SD = 27.9) and large scale models are also significantly different, but the means for the small and medium scales are not significantly different even at a 90% confidence level (p = .209).

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[39] This is particularly surprising due to the long length of the period simulated–40 years.

Experiment III: The third experiment was intended to explore the importance of the choice between market pricing mechanisms in market design. We utilized Model III (EPCandVERR model) which we had used in both previous experiments, retaining its default uniform-pricing setting for one model run, while changing that setting to a discriminatory-price setting to generate Model VI.

We find that the mean of Trade Volumes under the uniform-price mechanism is about 3,476MtCO$_2$ which is about 12% of the mean volume generated under the discriminatory mechanism (at TV = 30,226MtCO$_2$), and both systems differing very significantly even at a 99.99% confidence level. The two systems also differ very significantly in terms of average cost (AC = \$111 for the uniform system, and AC = \$61.8 for a discriminatory system), and volatility (SD = \$27 for uniform, and SD = \$44.7 for discriminatory) as can be expected just by observing the simulations themselves or the sheer magnitudes of their respective sample means.

Experiment IV: The aim of Experiment IV was to examine the role of a price cap in the carbon market. To know whether the level of the cap was important or not, we had to enbark on a series of trial-by-error runs to identify a level below which the cap would prevent trade within the virtual market. We discovered this to be at about \$100 (at \$90 the market witnessed no activity). This was the basis of our choice of \$100 as a starting point. We also ran simulations at caps of \$110 and \$150 in order to have an idea about how increases to those levels–while holding abatement-costs constant–would affect the volume of trade, cost of compliance, and volatility. The experiment was achieved just by adjusting the "CCEMF" slider on the left of the interface to suit each run.

We found the difference between sample means of Trade volumes to be highly significant at the 99% level of confidence only for caps of \$100 (TV = 28,297MtCO$_2$) and \$150 (TV = 20,621MtCO$_2$), slightly less significant at 95% for caps of \$110 (TV = 25,404) and \$150, and not significant even up to a 20% critical level for caps of \$100 and \$110. Similarly, the

means of average cost between the $100 (at AC = $46) and $150 (at AC = $104.8) caps and the $110 (at AC = $55) and $150 caps are highly significantly different, while the $100 and $110 caps are not significantly different. The means of all their respective volatilities are however significantly different at the 99% level at $39, $42, and $53 for $100, $110, and $150 caps respectively.

To check for robustness in all our results, we ran the Welch test which returned very similar F and p-values as the ordinary F-test and gives no indication that relaxing the statistical assumption of normally distributed errors affects our output in any significant way.

## 5.3     Discussion

We generally adjudge good market performance as higher trade volumes, lower average costs of compliance, and lower price volatilities, based on the intuition that a market in which allowances are thinly traded is likely to be ineffective in aiding GHG reductions, a market in which higher average costs prevail is a less cost effective one that erodes the central purpose of establishing a cap and trade system, and a market that is rife with high volatility of prices is a high-risk and unstable one which is undermined by its lack of predictability. In essence, we would normally expect the better-performing market to achieve higher volumes, lower costs and lower volatilities at least to some degree.  One paradox that arises from our study however is the fact that the average cost of compliance in the market appears to be lowest in most of the samples that feature the highest volatility, while high trade volumes seem to be mostly accompanied by the lowest costs in the same sample. Generally, the alternative market designs do not appear to perform consistently well across all three criteria and this implies that decision-makers have to compromise among the three measures of performance. For instance, we observe that lower costs are mostly associated with higher volatility. Therefore if regulators have a high priority for stability, they have to accept higher average costs within the market. In essence, it would be

misleading given the interaction among measures to conclude about performance based on any single measure. Each of the measures (volume, cost, and volatility) reflects a different aspect of market performance (target effectiveness, price effectiveness and stability respectively).

In terms of high trade volume and low price volatility, markets with offset credits alone (VERRonly) outperform both the pure EPC, and the joint EPC/VERR markets. However, the average cost of compliance within this market-type is also the highest–exceeding that of a joint market by about $7. Given a situation where CCEMFs are channeled into aggressive low carbon projects and research rather than being used for welfare payments to low-income families or other non-abatement purposes, high trade volume may become less important as a performance indicator, making cost of compliance the more prominent criterion. As such, making a choice about which criterion should be adhered to would depend on other realities in the market, as well as the established priority of regulators at a point in time.

It follows reason that the VERR model should be the most expensive, since offset developers are likely to invest in projects only if there is an attractive price incentive, and they will be willing to supply more at ever-higher prices. Unlike in many other markets, emitters are compelled to submit annual compliance reports and almost any price that is a premium below the CCEMF would be acceptable since the alternative will be to pay at the maximum CCEMF rate. Thus the CCEMF naturally establishes a market in which prices are sticky upwards, and the extent of volatility directly affects the extent to which those prices differ from the CCEMF and as such, the extent to which compliance costs are reduced in the market. An explanation for the afore-mentioned paradox might therefore be that higher volatility is a prerequisite for lower prices and compliance costs on average, and that the demand side has an incentive to procure more allowances thereby driving trade volume upwards, the lower prices are in the market.

Perhaps the greatest puzzle from this experiment is the fact that trade volumes are generally lower in the joint EPCandVERR market than in the EPConly market. This outcome is counter-intuitive–it appears natural that if a market is opened up to wider supply participation,

more units would be available for trade and consequently more units would be exchanged. It makes normal sense though that this market would exhibit the lowest cost since the free entry of more suppliers suggests that there may be more market competition and this is generally likely to result in price-competition particularly since the commodity being sold is essentially homogenous in nature and other sorts of competitive behavior such as branding and advertisement are unlikely to be useful. While the Total volumes in both markets are not statistically different, the fact that the EPConly market traded more on average than the joint market may be an indicator that the decline in prices due to the introduction of offset developers into the market may have come at a cost of oligopolistic capacity withholding to avert further price reductions. It may also imply that emitters have a lower incentive to reduce their emissions internally since they are aware that off-setters are offering allowances for sale in the market. In either case, implementation of the two policies appears to have an interaction and produces dividends only in terms of cost efficiency, while having a possible (unconfirmed) tendency towards reducing the quantity of allowances traded in the market.

Experiment II appears to statistically support a theory that the scale of the market matters in its performance. While it makes no practical sense to compare absolute trade volumes for this experiment, the fact that doubling the scale of the market results in a bit more than double of its trade volumes, and quadrupling it results in eight times its former volume implies the prevalence of scale dynamics in the model. Since we have made reasonable efforts to calibrate the model, this may indicate that such scale sensitivities exist in the real market, and increasing the scale of that market–possibly by expanding the scheme to include another province (like nearby Saskatchewan)–might yield benefits in terms of reduced compliance costs and increased volumes. Before we can extend this observation to the actual market however, it would be necessary to subject the model to some tighter calibration with survey based parametric data, in order to ascertain that the scale dynamics is not just a model peculiarity. If we were to hazard a guess at the reason why scale dynamics appear in this model however, we would be inclined to a

conjecture that it has to do with the power distribution of emissions among participants in our model. Since our model is a mere replication of emissions distribution in the actual population, it is likely to find similar scale sensitivities in the actual carbon market.

The successively lower prices (reductions of $4 and $10) perceivable in the models run on larger scales also seem consistent with the thesis that scale sensitivities exist. However, scale seems to impact prices a little less than it impacts volume, while it appears to be more strongly associated with increased volatility which is evident particularly between the medium and large scale models (an increase of $8 in volatility as opposed to $1 in the small to medium-scale).

In Experiment III, we find that the discriminatory-pricing model outperforms the uniform-pricing mechanism in both trading volume and average cost of compliance (a finding that seems to support earlier reports by Evans and Green (2003)), but underperforms in terms of its much higher volatility. However during the model runs, we also noticed that the discriminatory market often crashes, as does the uniform-pricing market, but takes a far longer time to rebound, and sometimes does not. Impressively low prices could therefore be misleading as a measure of good performance since it appears that they may have been borne of a persistent market failure. Consequently, the much higher trade volumes that the discriminatory mechanism boasts of may be attributable to panic-selling by suppliers when the price starts to fall, which further depresses the prices and carries the market into a long-term trough. The mechanism's significantly higher volatility measure also seems to support this possibility, while the fact that the average cost falls below the Average Cost of Abatement implies that suppliers might be incurring losses in offloading their inventory in order to escape a crashing market–a likely deterrent to investments in the near to medium future. Since participants within the mechanism pay what they bid and therefore have an incentive to bid more honestly, this raises an interesting (perhaps naive) question on whether honesty among participants is an unhealthy feature for markets or not.

Experiment IV was actually inspired by the negative effect that the currently low CCEMF cap ($15) seems to have on investment within the Alberta carbon market. However, in the scenario we examined we assumed a realistic average abatement cost ($75) and wondered how far above that cost a cap should be placed in order to encourage good market performance. Our simulations showed that if placed too close to the cost (that is less than 25% above the $75 cost), no trade occurs. However, if placed as high as $150, the level of volatility and average costs soar while the traded volume drops significantly relative to $100 and $110 caps. Although they yield far less average costs of compliance and lower volatilities, the $100 and $110 caps show average costs of compliance below average abatement costs. Barring technological advances that may reduce abatement costs, the excessively low compliance costs may as in Experiment III be an unhealthy phenomenon due to crashing prices which is likely to scare away investments from the market in the long-run and induce market failure. Based on the foregoing, a cap somewhere above $110 but below $150 may be most desirable, as long as it achieves a market price that is consistently above the average cost of abatement (providing some security for suppliers) while still being more cost effective than a $150 cap (providing some incentive for emitters to purchase).

Our findings suggest that trade-offs between GHG emissions reduction goals, cost effectiveness, and market volatility are likely to be important considerations in building a healthy, efficient and effective design for the Alberta carbon market. Also, lower compliance costs appears to be a sign of good performance only when accompanying volatility levels in the markets of concern are not significantly higher, as higher volatility may indicate crashing prices (as we observed under the discriminatory mechanism). Aspects of design such as the source of credits should be re-evaluated beyond common sense expectations, and policy combinations by the simultaneous use of tools such as the EPC and VERR may interact to cause counter-intuitive results, policy redundancy and even thin trading within the carbon market. We suggest the further examination of performance accruals due to increased scale within the market, and also suggest

that the discriminatory-pricing mechanism which is currently operational in an informal sense should be overhauled into a uniform-pricing mechanism to reduce the risk of a long term market collapse. Alternatively, it may also be rigorously re-examined with a view to understanding what aspect of its market design is responsible for the market's undesirably pattern. Our fourth major suggestion is that care should be taken when choosing a level of the price cap in the system, as performance of the system appears to be highly sensitive to the height of the cap relative to the average cost of abatement.

**Chapter 6: Conclusion**

At the beginning of this study, we identified two broad objectives namely: to build a simple model that realistically describes the carbon market in Alberta, and to gain an insight into the dynamics within the market based on data procured from our simulations on it. We found agent-based modeling to be a valuable resource in replicating salient features of the actual market such as heterogeneity of participating agents, imperfection and asymmetry in information, and the use of threshold rules rather than general-optimization frameworks in decision making and market coordination. We were able to achieve our goals by building a simple computational agent-based model, making efforts to calibrate it with empirical data, and conducting four experiments on it. Our findings appear strong and incisive and demonstrate the possibility of investigating a wide variety of issues even in young fledgling markets, afforded by Complex Adaptive Systems (CAS) modeling.

Our study contributes to extant literature in both academic and practical capacities. In a practical sense, we have examined an actual market within the context of its defining characteristics and identified issues in market design that are important and significantly related to good performance. We have also developed a flexible framework within which tangible analysis of various policy options can be undertaken. In essence, we have provided a dynamic tool that may be useful in aiding stakeholders as diverse as emitters, project developers, aggregators and especially market regulators, to better understand an ordinarily amorphous market. Furthermore, we have utilized the tool in answering 4 broad questions that constitute fundamental design issues concerning the market. At a minimum, our model serves as a starting point for an enhanced quality of discourse on carbon-market design issues, and can be easily adapted to fit new data and other carbon schemes (by modifying its easily accessible parameters), or other commodity markets (by modifying less accessible programming codes).

Our contribution to academic literature straddles two fields: economic theory and agent-based modeling. We add to the literature on economic theory by examining issues of market

design such as the effectiveness and efficiency of alternative policies regarding choice of instruments, scale of the market, and trading mechanism (particularly auction theory). While these are issues that have enjoyed lots of attention in other markets, they have not been sufficiently investigated in carbon markets due to the dearth of time-series data that is required for conventional research. Therefore our study also contributes to economic literature by giving additional evidence of the utility that may be derived from computational modeling methods that do not make unempirical assumptions of homogeneity in populations, gaussianity, or perpetuation of historical trends. In addition, we have also departed from the general practice among agent based modellers of emissions trading schemes, of coupling the emissions market with a related energy (wholesale electricity) market. While the model designs for many of these previous studies are commendable efforts that are well justified by the questions concerning market interactions that they seek to address, their characterisation is hardly useful for exploring our immediate questions. By adopting a multi-sectorial single-market framework, we may have (to the best of our knowledge) constructed the first compliance multi-sectorial single-market carbon-trading model.

In creating a model built on an agent-based modeling framework, our study also adds to the fast-growing literature on agent-based modeling through a modest operationalization of cellular automata, and the compact combination of primitive codes to create a simple model with multiple functionalities. However, within a complex-systems context, our main contribution to agent-based modeling lies in the variety of complex phenomenon that the model is capable of generating based on the behavior of agents who operate by very simple rules and can interact.

Notwithstanding these contributions, our study has some limitations which if addressed could significantly enhance its validity. Foremost among these is the extent of calibration in the models constructed. While we made efforts to calibrate the model to the actual market, certain parameters such as $Alpha_{f/m/c}$, demand coefficient, and propensity to invest were set based on qualitative and implied estimates rather than quantitative measures. In future studies, relying on

data from actual surveys to arrive at these estimates would greatly aid the validation of the model and may even enhance the quality of output from the model, thus making it useful as a predictive tool. The linear expectation-formation and demand models that we used in order to keep the model simple could be improved in future by investigating how expectations are formed by actual participants in the markets, and how their demand curves are shaped. Nevertheless, the linear approximation serves us well in erecting a very basic model.

In addition, the model suffers in part from an implicit assumption that variables such as the Alphas and demand coefficient remain at constant levels through time, whereas they are more likely to vary over time in reality. Moreover, the aggregate parameters such as economic growth rate are estimates given by government agencies which might be reliable for a short term period (say 5 years) but may be unreliable for a period of 40 years. These limitations do not however constitute severe injury to the model when it is used in scenario analysis (our use for it) rather than as a forecasting tool (which we advise against at least at the model's relatively crude level of development).

We also make the assumptions that all agents in the market neatly fall into either fundamental, momentum, or contrarian "outlooks" and that these outlooks are unflinchingly held all through the duration of a simulation. This is a most unrealistic, albeit convenient assumption which future studies should attempt to eliminate. In reality, people adapt in their attitudes and beliefs based on their interactions with other agents and perceptions of relative successes or failures of past strategies. Incorporation of genetic algorithms that actualize agent learning and evolution of strategies into this model might help in harnessing more realism in this respect, and this could be adopted in future studies. However, given the nature of our research questions, it is unlikely that our inferences were impacted much by this simplifying omission.

This study could be extended in a variety of ways that span theoretical and methodological considerations. Future studies could attempt alternative specifications of the elements of market design that we explored in order to see if our observations hold regardless of

the details in that element or only for a subset of specifications. For example, where we operationalized a uniform-price mechanism based on average-price computation of the effective price, a minimum-price variant could be substituted. This would give an insight into differences or similarities between these two variants of uniform-price mechanisms and aid better understanding of how they work.

Also, conditional on adequate calibration, econometric tests could be run on the time-series that emerge from the model in order to more rigorously examine the relationships among variables, and go beyond asking questions of the "which…?", "what-if" and "how…?" type to more revealing questions of the "by how much…?" variant.

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**Appendix A**
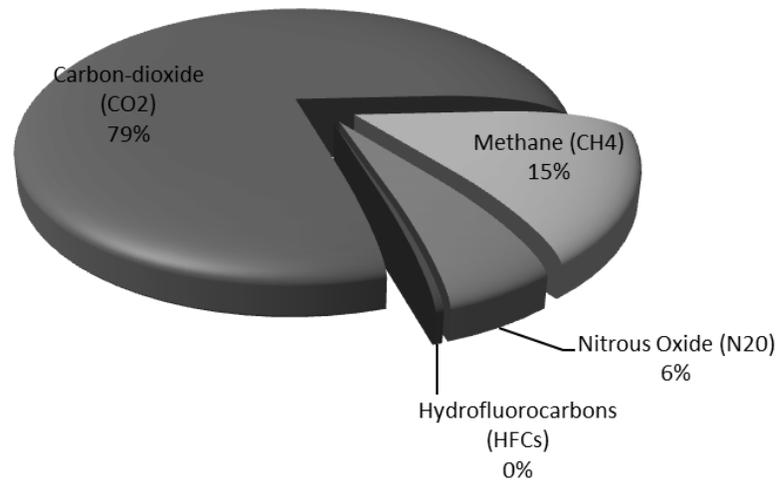


*Figure 1*. Contribution of 4 Gases to Total 2010 GHG Emissions in Alberta. Pie-chart constructed based on data sourced from UNFCCC (2012c, Table A14-19).

# Appendix B

## *Netlogo Codes for the Alberta Carbon Market*

```
Globals [
     CCEMF_Contribution              ;;; cumulative CCEMF purchased over time
     Aggregate_Demand                ;;; sum of all demand offers per period
     Aggregate_Supply                ;;; Sum of all supply offers per period
     Trade_volume                    ;;; (Min {AD, AS} ) per period
     uniform_price                   ;;; average price per period in a uniform setting
     Disc_price                      ;;; average price per period in a discriminatory setting
     Market_price                    ;;; effective average_price in either system
     ;; technical operators
     s                  ;;; experiment 1 indicator
     h                  ;;; experiment 2 indicator
     x                  ;;; New year indicator
     Total_trade_volume              ;;; sum of all aggregate trade_volumes  over time
     y                  ;;; sum [trade_volume * market_price] of patches per period
     y_list             ;;; sum of all y over time (2000)
     market_price_list               ;;; trend list for average price (over 2000 ticks)
     disc_price_list                 ;;; list of discriminatory price over periods
     disc_Ep_set                     ;;; set of expected prices for patches with demand > 0
     MAPLY                           ;;; moving-average-price-lastyear
     Trade_volume_list               ;;; trend list of trade volume (over 2000 ticks)
     Pt-1               ;;; last period's price
     Pt-2               ;;; price in 2 periods ago
     v                  ;;; sum of inhouse reduction of all patches
     o                  ;;; sum of all patches [inhouse reduction * Average_Cost_of_Abatement * 1.2]
     uniform_price_list              ;;; trend of uniform prices over time (used primarily to decide on LR investment)

     ]
     ;;;;;;; Slider globals :      CCEMF, INITIAL_PRICE, Target_multiple, Average_Cost_of_Abatement, Alphaf, Alpham, alphac,
demand_coefficient, propensity_to_invest,
     ;                   avg_annual_growth_rate - User can specify these
patches-own [
         Outlook            ;;; fundamental, momentum, contrarian (price outlook)
         total_reductions       ;;; Cumulative reductions over years
         inhouse_reduction       ;;; stock of non-market post-investment internal reductions
         total_supply           ;;; stock of quantity supplied by each agent
         Target             ;;; Annual Reduction Target of each firm
         IRC                ;;; Internal Reduction Capacity of each firm
         Reduced                ;;; Total emissions reduction in year excluding CCEMF_contribution
         Cost_of_Reduced        ;;; Previous stock + (Qty of trade * Price of trade)
         Sales_revenue          ;;; Previous stock + (Qty of trade * Price of trade)
         supply             ;;; Emitter's stock available for supply after meeting inhouse needs
         Autonomous_demand       ;;; The part of annual target that must be outsourced through permits or CCEMF (a)
         Demand             ;;; Emitter's request at current market price (a - bP)
         expected_price         ;;; Price at which each emitter bids based on outlook and memory
         CCEMF_cost             ;;; cost of CCEMF purchased to the firm
         investment         ;;; long term investments made by emitters
         trade              ;;; value of each bilateral trade in a price-discriminatory market
         quantity           ;; actual quantity traded in a price-discriminatory market
         ;; technical operators
         M                  ;;; Size distribution randomizing parameter
         t                  ;;; nominal used for holding certain tick-values at the micro-level
         w                  ;;; cost of inhouse reduction (inhouse reduction * Average_Cost_of_Abatement * 1.2)
         ]
breed [emitters emitter]
breed [offsetters offsetter]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to setup
 clear-all
 Ask patches                                             ;;; to set up world views with a random distribution
 [let n random 3
  if n = 0 [set outlook "fundamental"]
  if n = 1 [set outlook "momentum"]
  if n = 2 [set outlook "contrarian"]
 ]
```

Ifelse experiment1 = "EPConly" [set s 1] [set s 0.8]                    ;;; rule to identify the existence or absence of offsetters
                                                                        ;; s = 1 : EPC only  (meaning all patches are emitters)
                                                                        ;; s = 0.8 : EPC producers = 80%  VERR producers = 20%
  setup-huge_emitters                                                   ;;; setting-up all participants
  setup-large_emitters
  setup-small_emitters
  setup-offset
  Ask patches [if target < 0 [set IRC (irc + target) set target 0]]     ;;; to recognise advantage for companies that
produced more emissions in
                                                                        ;; 2005 than currently (they might have implemented low-carbon
technology)
  set market_price_list   []                                           ; setting up databases - lists (time-series) and sets
  set uniform_price_list []
  set disc_price_list []
  set MAPLY  []
  set trade_volume_list []
  set y_list []
  set disc_Ep_set []
  set uniform_price initial_price
  set disc_price initial_price

  reset-ticks
end
;-----------------------------------------------------------------------------------------------------------------------------------------
------
to setup-huge_emitters

  ask n-of round (s * .1 * count patches) patches [ set pcolor blue set M random-normal 1 0.48 if m < 0 [set m (- m)] set Target round
(M * 2120) set IRC round (M * 123)
                sprout-emitters 1 [set size 1 set color blue]
                ]
end
to setup-large_emitters
  ask n-of round (s * .2 * count patches) patches with [pcolor != blue] [set pcolor green set M random-normal 1 0.65 if m < 0 [set m (-
m)]  set Target round (M * 1155)
                set IRC round (M * 79 ) sprout-emitters 1 [set size .7 set color green]
                ]
  end
to setup-small_emitters
  ask n-of round (s * .7 * count patches) patches with [pcolor != blue and pcolor != green] [set pcolor pink  set M random-normal 1
0.73 if m < 0 [set m (- m)] set Target round (M * 93)
                set IRC round (M * 23) sprout-emitters 1 [set size .4 set color pink]
                ]
end
to setup-offset
if experiment1 != "EPConly"
 [ask patches with [pcolor = black] [set M random-normal 1 0.2 if m < 0 [set m (- m)]  sprout-offsetters 1 [set color black set shape
"offsetter" set size .5] ]
 ]
end
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to go
  tick
  set x (ticks / 50)                                                    ;;; this procedure calculates the beginning of a new year
  if x = round x
 [update_IRC_and_target_of_patches decide_on_longterm_investment]       ;;; Annual Revision by regulators
& capacity, Long term investment-
                                                                        ;; decision-making
 Ifelse Experiment3 = "Uniform-Clearing"                                ;;; Differentiating between uniform-pricing-
mechanism & Discriminatory
 [set market_price uniform_price effect_uniform_trades]
 [set market_price disc_price effect_discriminatory_trades]
   compile_market_price_trend                                          ;;; price trend compilation
  compute_price_expectations                                           ;; compute price expectations based on world views
 place_demand                                                          ;;; Place bid for credit demand
  ask turtles                                                          ;;; Current demand/supply color indicators
 [ifelse [demand] of patch-here > 0                                    ;; red means current demand offer, white means
current supply offer
  [set color red] [set color [pcolor] of patch-here]

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```
    if [supply] of patch-here > 0
    [set color white]
    ]
    if x = round x                                          ;;; Implies the end of a 50-tick period which signifies a year
    [year-end-decisions]
    if ticks = 2001 [stop]                                  ;;; End simulations after 40 years (i.e 50 ticks * 40 years
= 2000)
end
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
to update_IRC_and_target_of_patches                         ;;; IRC growth & Target growth over 40 years &
37years respectively
  if x > 1  [ask patches with [pcolor = blue] [set IRC IRC * 1.10 set reduced (reduced + IRC)]
    ask patches with [pcolor = green] [set IRC IRC * 1.05 set reduced (reduced + IRC)     ]
    ask patches with [pcolor = red] [set IRC IRC * 1.02 set reduced (reduced + IRC)        ]]
  if x > 3  [ask patches [set target target * avg_annual_growth_rate * target_multiple ] ]
  set trade_volume 0
end
to decide_on_longterm_investment
 if experiment1 != "VERRonly"                               ;;; For EPConly and EPC/VERR models
[if ticks >= 500
  [ask patches with [pcolor = blue]
  [if investment = 0 and supply < 0.2 * target and (mean MAPLY) > Average_Cost_of_Abatement
    and CCEMF > (Average_Cost_of_Abatement * 1.2)                        ;;; pti = 1 naive eagerness to invest/lack
of infor
    and random-float 1 <= propensity_to_invest              ;; pti = 0 means total unwillingness to invest
    [set investment (M * 50000) set t ticks]                 ;; 50MtCO2 project- this is only possible after
2020 & matures
  let p (investment - demand)                               ;; in five years
  if ticks = (t + 500) and demand < investment
  [set supply (supply + p) set reduced (reduced + demand) set demand 0 set investment 0 set t 0]       ;; huge supply placing
  ]
  ]
  ask patches with [pcolor = green]
  [ if investment = 0 and supply < .2 * target and (mean MAPLY) > Average_Cost_of_Abatement
    and CCEMF > (Average_Cost_of_Abatement * 1.2)
    and random-float 1 <= propensity_to_invest
    [set investment (M * 5000) set t ticks]                  ;;; i.e 5MtCO2 - this matures in three years
  let q (investment - demand)
  if ticks = (t + 300) and demand < investment
  [set supply (supply + q) set reduced (reduced + demand) set demand 0 set investment 0 set t 0]          ;; large supply placing NB:
Investment is price elastic
  ]                                                          ;; but supply is not itself elastic
  ask patches with [pcolor = red]
  [ if investment = 0 and supply < .2 * target and (mean MAPLY) > Average_Cost_of_Abatement
    and CCEMF > (Average_Cost_of_Abatement * 1.2)
    and random-float 1 <= propensity_to_invest
    [set investment (M * 500) set t ticks]                   ;;; i.e 500 KtCO2 - this matures in two years
  let r (investment - demand)
  if ticks = (t + 200) and demand < investment
  [set supply (supply + r)  set reduced (reduced + demand) set demand 0  set investment 0 set t 0]          ;; small supply placing
  ]
]
 ;Offset market supply-side: Long term investment rule:
 if experiment1 != "EPConly"                                ;;; For VERRonly and EPC/VERR models
 [ask patches with [pcolor = black]
  [if investment = 0 and (mean MAPLY) > Average_Cost_of_Abatement
    and CCEMF > (Average_Cost_of_Abatement * 1.20)
    and random-float 1 <= propensity_to_invest * .5 and aggregate_demand > 5000
    [set investment (M * 10 * (mean MAPLY - Average_Cost_of_Abatement)^ 2 ) set t ticks]            ;; Here we make
investment-size proportional to facilities' size
  if ticks = (t + 400) [set supply (supply + investment) set investment 0 set t 0]
  ask offsetters [ifelse supply > 0 [set color white] [ set color black]]          ;;; Supply indicator for offsetters: color is
set to white if
  ]                                                          ;; they have mature credits. Offsetters have no demand
 ]
end
;------------------------------------------------------------------------------------------------------------------------------------------
----------------
to compile_market_price_trend                              ;;; to compile time-series of price over time
  set market_price_list lput (market_price) market_price_list          ;; market price trend
```

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```
  let l length market_price_list
  let memory 50                                                      ;; memory length for the past year (1 year = 50 ticks)
  set uniform_price_list lput (uniform_price) uniform_price_list                    ;; uniform-price trend
  let r length uniform_price_list
  ifelse ((ticks) < memory)
   [set MAPLY sublist uniform_price_list  0 l]
   [set MAPLY sublist uniform_price_list (1 - memory) l]                             ;; 1 year trend : 1 year memory
  ifelse ((ticks) < 2)
  [set Pt-1 item 0 market_price_list]                                ;;; Market-Price in last trading-period
  [set Pt-1 item (l - 1) market_price_list
   set Pt-2 item (l - 2) market_price_list]                          ;; & Average-Price in second-to-last trading-
period
  ;;lets also calculate total trade volume for each simulation here
  set trade_volume_list lput (trade_volume) trade_volume_list                       ;;; The sum of trade volume is necessary
for
  let g length trade_volume_list                                     ;; evaluating market-performance
  set total_trade_volume sum trade_volume_list
ifelse experiment3 = "Uniform-Clearing"                              ;;; assigning different prices to their respective
systems
  [set y trade_volume * uniform_price] [set y trade_volume * disc_price]
set y_list lput (y) y_list                                          ;;; compiling a time-series for value of trades
 set disc_price_list lput (disc_price) disc_price_list               ;;; discriminatory-price trend
  end
;-------------------------------------------------------------------------------------------------------------------------------
----------------
to compute_price_expectations                                        ;;; Defining the way each emitter predicts price
based on its
ask patches with [outlook = "fundamental"]                           ;; outlook (world-view). Remember that
distribution is stochastically
[let change (alphaf * (Average_Cost_of_Abatement - Pt-1))            ;; assigned at onset (setup
stage)
  ifelse change > 0
  [set expected_price (Pt-1 + change)] [set expected_price Pt-1]
]
ask patches with [outlook = "momentum"]
[let change (alpham * (Pt-1 - Pt-2))
  ifelse change > 0
  [set expected_price (Pt-1 + change )] [set expected_price Pt-1]
]
ask patches with [outlook = "contrarian"]
 [let change (alphac * (Pt-1 - Pt-2))
  ifelse change > 0
  [set expected_price (Pt-1 + change)] [set expected_price Pt-1]
 ]
end
;-------------------------------------------------------------------------------------------------------------------------------
-----------------
to place_demand
  ask patches [if (target - reduced) > 0 and supply = 0 and expected_price < (CCEMF - 5)        ;;; Demand
Placement rules
        [set autonomous_demand (target - reduced)            ;;;; demand placed
          if demand_coefficient * expected_price < autonomous_demand
          [set demand autonomous_demand - (demand_coefficient * expected_price)]
        If supply < 0  [set supply 0]                                ;;; in-house clearing rule
        If demand > 0 and supply > demand [set supply (supply - demand) set reduced (reduced + demand)
         set inhouse_reduction (inhouse_reduction + demand)  set demand 0]
        If demand > 0 and supply <= demand [set demand (demand - supply) set reduced (reduced + supply)
         set inhouse_reduction (inhouse_reduction + supply) set supply 0]
        ]
        ]
  ask patches [set w (inhouse_reduction * Average_Cost_of_Abatement * 1.2)]        ;;; accounting for
inhouse reductions in computing
  set o sum [w] of patches                                          ;; the cost of abatement in interface
  set v sum ([inhouse_reduction] of patches)
end
;-------------------------------------------------------------------------------------------------------------------------------
------------------
to effect_uniform_trades
  set aggregate_demand sum [demand] of patches with [demand > 0]
  set Aggregate_supply sum [supply] of patches with [supply > 0]
```

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```
 If aggregate_demand <= aggregate_supply
  [let k 0                                                                    ;;;trigger to indicate that supply-side has been settled
   if aggregate_demand > 0 and aggregate_supply > 0
   [set trade_volume aggregate_demand                                         ;;; Effective-trade-volume determination
(AD <= AS)
    set uniform_price ((sum [demand * expected_price] of patches with [demand > 0]) / aggregate_demand)        ;; average price
determination under AD < AS
    let sellers patches with [supply > 0]                                     ;;; to mop-up all demand by settling supply
side
    let a count sellers
    let seller patches with [supply >= aggregate_demand]
    let chosen count seller
    let avgsalevol (aggregate_demand / a)
    let sellers2 patches with [supply >= avgsalevol]
    let b count sellers2
    let balance aggregate_demand - (avgsalevol * b)
    let sellers3 patches with [supply >= balance]
    let c count sellers3
    let sellers4 patches with [supply >= 0.5 * balance]
    let d count sellers4
    let sellers5 patches with [supply >= (1 / 3) * balance]
    let f count sellers5
    if chosen > 0
    [ask one-of seller
     [set supply (supply - aggregate_demand) set total_supply (total_supply + aggregate_demand)
      set sales_revenue sales_revenue + (aggregate_demand * uniform_price) set k 1
     ]
    ]
    if chosen = 0
    [ask sellers2
     [set supply (supply - avgsalevol) set total_supply (total_supply + avgsalevol)
      set sales_revenue sales_revenue + (avgsalevol * uniform_price) set k 1
     ]
    ]
    if balance > 0 and c > 0                                                  ;; In case some suppliers have less than the
average quantity
     [ask one-of sellers3                                                     ;; but one or some can absorb the whole balance
      [set supply (supply - balance) set total_supply (total_supply + balance)
       set sales_revenue sales_revenue + (balance * uniform_price) set k 1
      ]
     ]
    if balance > 0 and c = 0 and d = 1                                        ;; In case some suppliers have less than the
average quantity
     [ask n-of 1 sellers4                                                     ;; but only 1 can absorb the balance - then we give
that one
      [set supply (supply - (0.5 * balance)) set total_supply (total_supply + (0.5 * balance))    ;; and share the balance
again
       set sales_revenue sales_revenue + (0.5 * balance * uniform_price) set k 1
      ]
     ]
    if balance > 0 and c = 0 and d = 2                                        ;; In case some suppliers have less than the
average quantity
     [ask n-of 2 sellers4                                                     ;; but none can absorb the balance - then we share
among 2
      [set supply (supply - ((1 / 2) * balance)) set total_supply (total_supply + ((1 / 2) * balance))
       set sales_revenue sales_revenue + ((1 / 2) * balance * uniform_price) set k 1
      ]
     ]
    if balance > 0 and c = 0 and f = 3                                        ;; In case some suppliers have less than the
average quantity
     [ask n-of 3 sellers5                                                     ;; but no two can absorb the balance - then we share
among 3
      [set supply (supply - ((1 / 3) * balance)) set total_supply (total_supply + ((1 / 3) * balance))
       set sales_revenue sales_revenue + ((1 / 3) * balance * uniform_price) set k 1
      ]
     ]
    if k = 1                                                                  ;; i.e if supply has been settled
   [ask patches with [demand > 0]
    [set reduced (reduced + demand)                                          ;; demand-side settlement
     set cost_of_reduced (cost_of_reduced + (demand * uniform_price))
```

```
      ]
   ]]
   ]
  If aggregate_demand > aggregate_supply
  [let k 0                                                        ;;; trigger to indicate if demand has been settled
   if aggregate_demand > 0 and aggregate_supply > 0
   [set trade_volume aggregate_supply                                        ;;; Effective-trade-volume determination
(AD > AS)
    set uniform_price (sum [supply * expected_price] of patches with [supply > 0]) / aggregate_supply          ;; market price
determination under AD > AS]
   let buyers patches with [demand > 0]                                       ;;; to mop-up all demand by settling supply
side
   let a count buyers
   let buyer patches with [demand >= aggregate_supply]
   let chosen count buyer
   let avgsalevol aggregate_supply / a
   let buyers2 patches with [demand >= avgsalevol]
   let b count buyers2
   let balance aggregate_supply - (avgsalevol * b)
   let buyers3 patches with [demand >= balance]
   let c count buyers3
   let buyers4 patches with [demand >= 0.5 * balance]
   let d count buyers4
   let buyers5 patches with [demand >= 1 / 3 * balance]
   let f count buyers5

   if chosen > 0
   [ask one-of buyer
    [set reduced (reduced + aggregate_supply) set cost_of_reduced (cost_of_reduced + (aggregate_supply * uniform_price))
     set k 1
     ]
    ]
   if chosen = 0
   [ask buyers2
    [set reduced (reduced + avgsalevol) set cost_of_reduced (cost_of_reduced + (avgsalevol * uniform_price))
     set k 1
     ]
    ]
   if balance > 0 and c > 0                                         ;; In case some buyers have less than the
average quantity
   [ask one-of buyers3                                             ; but one or some can absorb the whole
balance
    [set reduced (reduced + balance) set cost_of_reduced (cost_of_reduced + (balance * uniform_price))
     set k 1
     ]
    ]
   if balance > 0 and c = 0 and d = 1                                  ;; In case some buyers have less than the
average quantity
   [ask n-of 1 buyers4                                             ; but only 1 can absorb the balance - then we
give that one
    [set reduced (reduced + (0.5 * balance)) set cost_of_reduced (cost_of_reduced + (0.5 * balance * uniform_price))       ; and share
the balance again
     set k 1
     ]
    ]
   if balance > 0 and c = 0 and d = 2                                  ;; In case some buyers have less than the
average quantity
   [ask n-of 2 buyers4                                             ; but none can absorb the balance - then we
share among 2
    [set reduced (reduced + ((1 / 2) * balance)) set cost_of_reduced (cost_of_reduced + ((1 / 2) * balance * uniform_price))
     set k 1
     ]
    ]
   if balance > 0 and c = 0 and f = 3                                  ;; In case some buyers have less than the
average quantity
   [ask n-of 3 buyers5                                             ; but no two can absorb the balance - then we
share among 3
    [set reduced (reduced + ((1 / 3) * balance)) set cost_of_reduced (cost_of_reduced + ((1 / 3) * balance * uniform_price))
     set k 1
     ]
```

```
    ]
    if k = 1                                                          ;; i.e if demand has been settled
   [ask patches with [supply > 0]
   [set total_supply total_supply + supply                           ;; supply-side settlement
    set sales_revenue sales_revenue + (supply * uniform_price)
   ]
  ]]
 ]
 let l Aggregate_supply - Aggregate_demand
 if l < 0 [set l (- l)]
  If Aggregate_demand < Aggregate_supply
   and(Aggregate_supply - Aggregate_demand) > 1000                    ;;; market price responses to As & AD
inequilibrium even without trade
   and (Aggregate_supply - Aggregate_demand) < 10000
   [set uniform_price (uniform_price - (.0001 * l))]
  If (Aggregate_supply - Aggregate_demand) > 10000
   and (Aggregate_supply - Aggregate_demand) < 100000
   [set uniform_price (uniform_price - (.0002 * l))]
  If (Aggregate_supply - Aggregate_demand) > 100000
   [set uniform_price (uniform_price - (.0003 * l))]
  If uniform_price < 0.1 [set uniform_price 0.1 ]
  If uniform_price > CCEMF [set uniform_price CCEMF - 1 ]
  If Aggregate_demand > Aggregate_supply
   and(Aggregate_demand - Aggregate_supply) > 1000                    ;;; market price responses to As & AD
inequilibrium even without trade
   and (Aggregate_demand - Aggregate_supply) < 10000
   [set uniform_price uniform_price + (.0001 * l)]
  If (Aggregate_demand - Aggregate_supply) > 10000
   and (Aggregate_demand - Aggregate_supply) < 100000
   [set uniform_price uniform_price + (.0002 * l)]
  If (Aggregate_demand - Aggregate_supply) > 100000
   [set uniform_price uniform_price + (.0003 * l)]
  If uniform_price < 0.1 [set uniform_price 0.1]
  If uniform_price < 0.1 [set uniform_price 0.1 ]
  If uniform_price > CCEMF [set uniform_price CCEMF - 1]
end
;--------------------------------------------------------------------------
to effect_discriminatory_trades
 set aggregate_demand sum [demand] of patches with [demand > 0]
 set Aggregate_supply sum [supply] of patches with [supply > 0]
 define_disc_micros
 define_disc_aggregates
end
to define_disc_micros
Ask patches
[set expected_price (expected_price + ((m / 10) * expected_price))]   ;;; We made the assumption here that bigger
emitters are likelier to bid
                                                ; higher than smaller emitters because they have higher targets and
                                                ; more desperation for credits. m is the same randomising parameter
that
set disc_Ep_set [expected_price] of patches with [demand > 0]         ; we used in set-up to specify the population
distribution of the market
 If any? patches with [supply > 0] and any? patches with [demand > 0] ;;; does supply exist? does demand exist?
 [Ask patches with [supply > 0]                                       ;; if yes, ask one supplier
  [If any? patches with [demand > 0 and expected_price = max disc_Ep_set]
  [let g one-of patches with [demand > 0 and expected_price = max disc_Ep_set]
   If [demand] of g <= supply                                         ;;; if demand is less than or equal to supply
   [set supply (supply - [demand] of g) set total_supply (total_supply + [demand] of g)
    set sales_revenue (sales_revenue + ([demand] of g * max disc_Ep_set))
    ask g                                                             ;; pick the patch with highest price and a demand for credits
    [set reduced (reduced + demand)
     set cost_of_reduced (cost_of_reduced + (demand * max disc_Ep_set))
     set trade ( max disc_Ep_set * demand)
     set quantity (demand )
     set demand 0
    ]
   ]
  ]
  If [demand] of g > supply                                           ;;; if demand is greater than supply
   [set total_supply (total_supply + supply)
    set sales_revenue (sales_revenue + (supply * max disc_Ep_set))
```

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```
    set trade (max disc_Ep_set * supply)
    set quantity supply
    ask g
    [set demand (demand - [supply] of myself)
     set reduced (reduced + [supply] of myself)
     set cost_of_reduced (cost_of_reduced + ([supply] of myself * max disc_Ep_set))
    ]
    set supply 0
   ]
  ]
 ]
]
end
;----------------------------------------------------------------------------------------------------------------------------------------
--------------
to define_disc_aggregates
 let l Aggregate_supply - Aggregate_demand
 if l < 0 [set l (- l)]
 ifelse sum [trade] of patches > 0 and sum [quantity] of patches > 0
 [set disc_price sum [trade] of patches / sum [quantity] of patches]
 [set disc_price 0.1]
ifelse aggregate_demand <= aggregate_supply
[ set trade_volume aggregate_demand] [set trade_volume aggregate_supply]
  If Aggregate_demand < Aggregate_supply
and(Aggregate_supply - Aggregate_demand) > 1000 ;;; market price responses to As & AD inequilibrium even without
                                      ;trade
    and (Aggregate_supply - Aggregate_demand) < 10000
    [set disc_price (disc_price - (.0001 * l))]
   If (Aggregate_supply - Aggregate_demand) > 10000
    and (Aggregate_supply - Aggregate_demand) < 100000
    [set disc_price (disc_price - (.0002 * l))]
   If (Aggregate_supply - Aggregate_demand) > 100000
    [set disc_price (disc_price - (.0003 * l))]
   If disc_price < 0.1 [set disc_price 0.1 ]
   If disc_price > CCEMF [set disc_price CCEMF - 1 ]
   If Aggregate_demand > Aggregate_supply
and(Aggregate_demand - Aggregate_supply) > 1000 ;;; market price responses to As & AD inequilibrium even without
                                      ;trade
    and (Aggregate_demand - Aggregate_supply) < 10000
    [set disc_price disc_price + (.0001 * l)]
   If (Aggregate_demand - Aggregate_supply) > 10000
    and (Aggregate_demand - Aggregate_supply) < 100000
    [set disc_price disc_price + (.0002 * l)]
   If (Aggregate_demand - Aggregate_supply) > 100000
    [set disc_price disc_price + (.0003 * l)]
   If disc_price < 0.1 [set disc_price 0.1]
   If disc_price < 0.1 [set disc_price 0.1 ]
   If disc_price > CCEMF [set disc_price CCEMF - 1]
end


;----------------------------------------------------------------------------------------------------------------------------------------
-------------------

to year-end-decisions                                    ;;;; to clear annual-target balance by buying CCEMF
Contribution
    ask patches [ set total_reductions total_reductions + reduced]
    set CCEMF_contribution (ccemf_contribution +                        ;;; to take stock of Global CCEMF
     (sum [target - reduced] of patches with [target - reduced > 0] * ccemf))
    ask patches with [(target - reduced) > 0]                           ;; to take stock of individual CCEMF costs
    [set ccemf_cost ccemf_cost + ((demand) * ccemf)  set reduced reduced + (demand)]           ;;;;  Final account clearing for all
patches at year end
    ask patches [set reduced 0 set demand 0]
   end
;--------------------------------------------------------------------------------
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
```

Table 1

*Pledges and Standardized 2020 Targets of Alberta Provinces and Territories*

| Province/Territory | Pledged Target[a] | Standardized target (1990)[b] |
| --- | --- | --- |
| British Columbia | 33% below 2007 | 27.5% below 1990 |
| Alberta | 50 Mt below BAU[c] | 42% above 1990 |
| Saskatchewan | 20% below 2006 | 12.4% below 1990 |
| Manitoba | 15% below 2005 | 13.3% below 1990 |
| Ontario | 15% below 1990 | 15% below 1990 |
| Quebec | 20% below 1990 | 20% below 1990 |
| New Brunswick | 10% below 1990 | 10% below 1990 |
| Nova Scotia | 10% below 1990 | 10% below 1990 |
| Newfoundland | 10% below 1990 | 10% below 1990 |
| Prince Edward Island | 10% below 1990 | 10% below 1990 |

*Note.*

[a] is sourced from Canada's Emissions Trends 2012, an Environment Canada (2012) report.

[b] is computed by the formula–Pledged target / (Base year Emissions / 1990 Emissions from Table 1).

[c] Estimated BAU = 285MtCO$_2$ (Environment Canada, 2012, Table 17).

Table 2

*Trend of GHG Emissions in Canada (1990–2010)*

| Province/ Territory | Annual Emissions KtCO$_2$e | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1990 | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| Newfoundland & Labrador | 9,230 | 8,660 | 10,400 | 9,400 | 10,600 | 9,900 | 9,900 | 8,860 |
| Prince Edward Island | 1,960 | 2,200 | 2,240 | 2,120 | 2,140 | 2,040 | 1,960 | 1,960 |
| Nova Scotia | 19,100 | 21,500 | 23,700 | 20,900 | 21,900 | 20,500 | 19,500 | 20,400 |
| New Brunswick | 15,900 | 20,800 | 22,500 | 19,800 | 19,900 | 18,400 | 18,600 | 18,600 |
| Quebec | 83,800 | 84,600 | 86,100 | 84,800 | 88,000 | 86,100 | 84,300 | 82,000 |
| Ontario | 176,000 | 206,000 | 206,000 | 196,000 | 200,000 | 191,000 | 166,000 | 171,000 |
| Manitoba | 18,300 | 21,000 | 20,600 | 20,700 | 21,300 | 21,200 | 19,800 | 19,800 |
| Saskatchewan | 43,200 | 64,500 | 69,900 | 69,400 | 71,800 | 73,300 | 72,600 | 72,100 |
| *Alberta* | 166,000 | 219,000 | 228,000 | 233,000 | 248,000 | 240,000 | 232,000 | 233,000 |
| British Columbia | 49,400 | 61,900 | 63,100 | 61,000 | 59,400 | 59,800 | 58,300 | 56,100 |
| Northwest Territories | 1,200 | 1,420 | 1,590 | 1,830 | 2,140 | 1,850 | 1,350 | 1,330 |
| Nunavut | 270 | 349 | 340 | 417 | 539 | 548 | 443 | 447 |
| Totals | 584,360 | 711,929 | 734,470 | 719,367 | 745,719 | 724,638 | 684,753 | 685,597 |

*Note*. Extracted from National Inventory Report (2012) 1990–2010—Part 3 (UNFCCC, 2012c)

Table 3

*Facility-Reported 2010 GHG Emissions by Province*

| Province | Number of Facilities | Total Emissions (ktCO$_2$e) | Percentage of Total Emissions (%) |
|---|---|---|---|
| Newfoundland & Labrador | 8 | 4546 | 2 |
| Prince Edward Island | 1 | 63 | 0 |
| Nova Scotia | 12 | 10602 | 4 |
| New Brunswick | 15 | 8228 | 3 |
| Quebec | 78 | 20675 | 8 |
| Ontario | 141 | 56210 | 21 |
| Manitoba | 12 | 1891 | 1 |
| Saskatchewan | 34 | 22794 | 9 |
| ***Alberta*** | ***163*** | ***122529*** | ***47*** |
| British Columbia | 68 | 13652 | 5 |
| Northwest Territories | 4 | 545 | 0 |
| Nunavut | 1 | 135 | 0 |
| Totals | 537 | 261869 | 100 |

*Note*. Sourced from *UNFCCC (2012c).*

Table 4

*Top 58 Alberta Emitters and their Emissions in 2010*

| Reporting Company | Emissions |
|---|---|
| TransAlta Generation Partnership | 23,734,954.00 |
| Syncrude Canada Ltd. | 12,707,889.00 |
| Suncor Energy Oil Sands Limited Partnership | 11,963,877.00 |
| Alberta Power (2000) Ltd. | 9,890,990.00 |
| Capital Power Generation Services Inc. | 9,307,001.00 |
| Canadian Natural Resources Limited | 6,404,638.00 |
| Imperial Oil Resources | 6,127,573.00 |
| Shell Chemicals Canada Ltd | 5,857,379.00 |
| Nexen Inc. | 3,678,537.00 |
| NOVA Chemicals Corporation | 2,775,892.00 |
| Cenovus FCCL Ltd., as operator for FCCL Partnership | 2,403,706.00 |
| Agrium Inc. | 2,081,182.00 |
| Nova Gas Transmission Ltd. | 1,671,003.00 |
| ATCO Power Canada Ltd. | 1,662,457.00 |
| Canadian Fertilizers Limited | 1,551,389.00 |
| Dow Chemical Canada ULC | 1,418,321.00 |
| TransCanada Energy Ltd. | 1,356,072.00 |
| Keyera Corp | 1,129,764.00 |
| Milner Power Limited Partnership by its GP Milner Power Inc. | 1,039,390.00 |
| Air Products Canada Ltd. | 980,920.00 |
| Lafarge Canada Inc. | 907,730.00 |
| Husky Oil Operations Limited | 863,484.00 |
| Devon Canada Corporation | 845,455.00 |
| Lehigh Cement, a Division of Lehigh Hanson Materials Ltd. | 795,449.00 |
| SemCams ULC | 761,554.00 |
| ConocoPhillips Canada Resources Corp. | 716,662.00 |
| MEG Energy Corp. | 697,411.00 |
| Alliance Pipeline Ltd. | 552,322.00 |
| Air Liquide Canada Inc. | 429,627.00 |
| Orica Canada Inc. | 416,532.00 |
| Inter Pipeline Extraction Ltd. | 412,284.00 |
| Encana Corporation | 399,054.00 |
| Spectra Energy Midstream Corporation | 390,947.00 |
| Talisman Energy Inc. | 334,362.00 |

*(Table 4 contd.)*

| Reporting Company | Emissions |
|---|---|
| City of Medicine Hat | 327,943.00 |
| Connacher Oil and Gas Limited | 309,986.00 |
| Taylor Processing Inc. | 303,620.00 |
| Sherritt International Corporation | 295,050.00 |
| Pengrowth Energy Corporation | 277,769.00 |
| Calgary Energy Centre No. 2 Inc. | 265,248.00 |
| Alberta Envirofuels Inc. | 259,679.00 |
| Japan Canada Oil Sands Limited | 252,345.00 |
| West Fraser Mills ltd. | 247,600.00 |
| MEGlobal Canada Inc. | 223,035.00 |
| Foothills Pipe Lines Ltd. | 201,955.00 |
| Coal Valley Resources Inc. | 195,829.00 |
| University of Alberta Heating Plant | 190,226.00 |
| Graymont Western Canada Inc. | 156,348.00 |
| INEOS Canada Partnership | 136,770.00 |
| Blaze Energy Ltd. | 129,175.00 |
| TAQA NORTH Ltd. | 122,916.00 |
| Teck Coal Limited | 120,632.00 |
| Apache Canada Ltd. | 118,199.00 |
| Weyerhaeuser Company Limited | 117,123.00 |
| Alberta-Pacific Forest Industries Inc. | 111,283.00 |
| Baymag Inc. | 107,031.00 |
| Cancarb Ltd. | 105,411.00 |
| Daishowa-Marubeni International Ltd-Peace River Pulp | 100,283.00 |

*Note*. Extracted from emissions data reported by Environment Canada (2010).

Table 5

*Calculation table for Target reduction and Natural Internal Reduction Capacity of Alberta's 58 Top Emitters in 2010*

| Class | No of firms | 2010 Emissions | Percentage of Total Emissions | 2005 Class Emissions | 2010 Class Average | SD Of 2010 Emissions | 12% below 2005 baseline | Necessary Target reduction | Natural Internal reduction Capacity |
|---|---|---|---|---|---|---|---|---|---|
| | (A) | (B) | (C) | (D) | (E = B/A) | (F=SD[B]) | (G=0.88 * {D/A}) | (H= E-G) | (I= E*x) |
| Top 10% | 6 | 74,009,349 | 0.61 | 69,646,028 | 12,334,892 | 6,009,108 | 10,214,751 | 2,120,141 | 123,349 |
| Next 20% | 12 | 31,713,275 | 0.26 | 21,985,043 | 2,642,773 | 1,718,380 | 1,488,218 | 1,154,555 | 79,283 |
| Next 70% | 40 | 15,218,639 | 0.13 | 14,724,645 | 380,466 | 279,949 | 287,949 | 92,517 | 22,828 |

*Note*. Derived from Environment Canada (2010) Data. Corporation emissions were obtained by adding facilities' emissions based on ownership.

Table 6

*Parameter settings for Experiments I–IV*

| Experiment | Experiment 1 | Experiment 2 | Experiment 3 | Experiment 4 |
|---|---|---|---|---|
| CCEMF [$] | 110 | 110 | 110 | 100 {15} / 110 {16} / 150{17} |
| Initial_Price [$] | 76 | 76 | 76 | 76 |
| Avg_annual_growth_rate [multiple] | 1.028 | 1.028 | 1.028 | 1.028 |
| Average_cost_of_abatement | 75 | 75 | 75 | 75 |
| Target_multiple | 1.02 | 1.02 | 1.02 | 1.02 |
| Alphaf | 0.6 | 0.6 | 0.6 | 0.6 |
| Alpham | 0.5 | 0.5 | 0.5 | 0.5 |
| Alphac | 0.5 | 0.5 | 0.5 | 0.5 |
| demand_coefficient | 3 | 3 | 3 | 3 |
| propensity_to_invest | 0.25 | 0.25 | 0.25 | 0.25 |
| Experiment I tab | EPConly {1,2,3}/ VERRonly {4,5,6} / EPC&VERR {7,8,9} | EPC&VERR | EPC&VERR | EPC&VERR |
| World Size | EPC - 8*8 / VERRonly & EPCandVERR - 9*9 | 9*9 {10} / 16*8 {11} / 16*16 {12} | 9*9 | 9*9 |
| Experiment III tab | Uniform-pricing | Uniform-pricing | Uniform-pricing {13} /Discriminatory Pricing {14} | Discriminatory |

*Note*. { } = Group number in experiment; X*X = Torus dimensions.

Table 7

*LSD Post-Hoc Test (Multiple Comparisons) Outputs*

| Experiment | Model Name | Performance indicator (Means) | | |
|---|---|---|---|---|
| | | TV | AC | SD |
| Experiment 1 | EPC | 5,816 | 114.6** | 23** |
| | VERR | 13,500** | 117.63** | 8** |
| | EPC & VERR | 4,049 | 110.0** | 28** |
| Experiment 2 | Small | 3,476** | 111** | 27 |
| | Medium | 8,024** | 107** | 28 |
| | Large | 24,834** | 98.8** | 36** |
| Experiment 3 | Uniform | 3,476** | 111.0** | 27** |
| | Discriminatory | 30,226** | 61.8** | 44** |
| Experiment 4 | $100 | 28,297 | 46.78 | 39* |
| | $110 | 25,404 | 55.99 | 42* |
| | $150 | 20,621* | 104.78** | 53** |

*Note*. Extracted from SPSS output. Asterisks show values that are significantly different. TV = Total Volume, AC = Average Cost, and SD = Standard Deviation.

\* $p < .01$, two-tailed. \*\* $p < .001$, two-tailed.