The Performance of Intensity Caps under Uncertainty

by

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1 Introduction

Regulated limits on emissions can take the form of absolute caps on the total level of emissions, or caps on the emissions intensity of some measure of output, hereafter referred to as intensity caps. The debate about whether or not to tie emissions limits to output is becoming increasingly important, particularly when it comes to policies aimed at reducing emissions of greenhouse gases (GHGs). In this context, the attractiveness of intensity caps is based largely on the argument that higher output should be associated with a higher level of allowable emissions, so as to reduce the risk of unacceptably high compliance costs (Pizer 2005).

The overarching purpose of this paper is to examine the properties of absolute emissions caps and intensity caps, both from a practical and theoretical perspective. Most importantly though, we intend to contribute to the literature in this area by exploring the properties of the two forms of emissions limits within a specific theoretical context. Using a simple analytical model based on Weitzman's (1974) prices versus quantities model, we examine the welfare implications of absolute and intensity caps when there is uncertainty about abatement costs (resulting from uncertainty about business-as-usual (BaU) emissions), and when abatement costs are a function of absolute (as opposed to relative) abatement. We find that in this context, the intensity cap will always dominate the absolute cap and will also dominate a price instrument (i.e. emissions tax) for a wide range of relevant parameter values.

Though we find that the intensity cap always dominates the absolute cap, the cost savings from the use of the intensity cap will be greatest when the marginal environmental damage (MED) curve is relatively flat, the intercept of the MED curve is low, uncertainty on BaU emissions is high and the marginal abatement cost (MAC) curve is relatively steep. Choosing between the intensity cap and the price instrument depends on most of the same key parameters: the intensity cap is most likely to dominate when the MED curve is steep, the intercept of the MED curve is low, and uncertainty on BaU emissions is high.

We attribute our results to the fact that the intensity cap, as presented in our model, is a flexible instrument which lies between a price instrument and an absolute cap. Specifically, the intensity cap allows both the emissions price and emissions levels to vary in response to changes in BaU emissions, while the other two instruments necessarily hold one of the two constant. This result stems from our assumptions about the nature of marginal abatement costs, and is in contrast to key papers in the literature (e.g. Quirion 2005) which find that intensity caps are essentially identical to price instruments.

This paper is organized as follows. Section 2 provides an overview of existing regulatory systems which are based on absolute caps or intensity caps. The focus of the section is on emissions trading systems, which are rapidly becoming the dominant instruments for implementing emissions limits. Section 3 surveys the literature comparing absolute and intensity caps. It is divided into two sections covering the two fundamentally different branches of the literature. The first of these branches examines absolute and intensity caps in the context of certainty, and the second does so in the context of uncertainty. In section 4, we develop and solve our model, and analyze the ranking and relative performance of the three instruments in detail. Section 5 concludes.

2 Background

The current debate between absolute and intensity emissions caps is directly related to the secondary issue of instrument choice, in that each type of cap is associated with a particular approach to emissions trading. Specifically, absolute caps are the basis for 'standard' cap-and-trade systems, while intensity caps are the basis for what we will refer to as intensity-based systems.[1] With more and more governments looking to emissions trading as a means of addressing environmental problems, the issue of choosing between these two approaches is becoming more and more relevant. This section will provide basic descriptions of each type of system[2], highlighting the key similarities and differences between them. It will also present notable examples of existing systems, and conclude by identifying major trends as well as lessons that have been learned about trading system design.

2.1 Cap-and-Trade and Intensity-Based Systems

Cap-and-trade systems work as follows. First, the regulator chooses an overall target quantity of emissions for a set of sources (often a particular industry or set of industries). They then distribute an equivalent number of emissions allowances (measured in units of emissions) to the firms, using one of several potential allocation methods. The simplest distribution schemes are free allocation based on historical emissions (grandfathering) and allocation by auction. Firms are free to buy and sell allowances, but can only emit as much pollution as is designated by the number of allowances that they hold. In practice, the regulator generally requires firms to surrender or 'retire' allowances in accordance with their emissions over a given compliance period (typically a year).

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[1] These systems are also referred to as rate-based emissions trading systems or tradable performance standards.

[2] For simplicity, we will restrict our focus to systems which regulate air emissions.

Unlike cap-and-trade systems, intensity-based systems do not fix the aggregate level of emissions, but rather the emissions intensity of output. Intensity-based systems involve an implicit baseline emissions profile that is determined by the fixed emissions intensity rate multiplied by output. Firms which reduce their emissions below their implicit baseline are granted emissions credits[3], which can then be sold to other firms whose emissions have exceeded their baselines.

As emissions trading systems, both cap-and-trade and intensity-based systems share certain key features. The first is that under both systems, firms will abate until their marginal abatement cost is equal to the allowance (or credit) price. Thus, marginal abatement costs will be equalized across firms, implying an efficient distribution of abatement effort. The great deal of flexibility which firms have in achieving the environmental target[4] means that both systems effectively transfer the burden of micro-managing abatement activities from the regulator to the firms. Both systems require relatively little information on the part of the regulator, and can (if the design is kept simple) be fairly easy to implement relative to most command-and-control regulatory regimes.

While both systems may have advantages in terms of economic efficiency, informational requirements and administrative simplicity relative to some other (non-market based) regulatory approaches, the differences between them are nonetheless important. One of the strengths of cap-and-trade systems is that they only require the regulator to monitor firms' emissions, while intensity based systems require monitoring of both emissions and output (however defined). Administrative and

[3] The term 'credit' is typically used instead of 'allowance' or 'permit' in the context of intensity-based systems, since they are a form of baseline-and-credit system. Baseline-and-credit systems differ from standard cap-and-trade systems in that credits are only generated when firms deviate from some baseline allowable emissions level. For more on baseline-and-credit systems, see (among others) Dewees (2001), Stavins (2003a), Fischer (2005), Tietenberg (2006).

[4] Not only do firms have the option of adjusting their permit holdings in response to changing circumstances, but they also enjoy the freedom of choosing for themselves the most appropriate method(s) of abating emissions (i.e. switching to cleaner fuels and inputs, adjusting production processes and improving energy efficiency, investing in specific abatement technologies, etc.). The exception to this is that in intensity-based systems, firms do not face an incentive to reducing emissions by reducing output. This issue will be addressed further in Section 3.

transactions costs may be higher under intensity-based systems because the issuance of credits requires the regulator or some third party to verify that the firm in question has indeed reduced emissions below its baseline.[5]

While the administrative process of issuing credits can be more burdensome under an intensity-based system, it has the advantage of largely avoiding the politically contentious process of determining allowance allocations in a cap-and-trade system.[6] It can also be much easier to accommodate new entrants in a fair manner in an intensity-based system, where credits are not issued on the basis of historical emissions (as in many cap-and-trade systems) (Rosenzweig and Varilek 2003).

2.2 Offsets

Offset provisions can be incorporated into the design of both cap-and-trade systems and intensity-based systems. Offsets allow firms to fund emissions-reductions projects in sectors that are not covered by the emissions trading system.[7] Based on the emissions reductions achieved through these projects, offsets are generated which can then be used by firms to meet their regulatory obligations, in the same way as standard allowances (for cap-and-trade systems) and credits (for intensity-based systems).

The key benefit of offsets is that they gives firms additional flexibility in achieving their emissions reductions targets, and can thereby lower compliance costs. This is because they allow firms to take advantage of inexpensive abatement opportunities that may exist in sectors not covered by the

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[5] Not surprisingly, this is a problem that applies to all baseline-and-credit systems, not just intensity-based systems. Early experience with baseline-and-credit systems by the U.S. Environmental Protection Agency (EPA) (see note 9) provided evidence of this. The EPA's Emissions Trading Program (ETP) (see note 10) suffered from high transactions costs associated with verification and crediting (in combination with regulatory approvals necessary for each trade). The results were low levels of trading activity and cost savings that were low relative to their potential (Hahn and Hester 1989).

[6] Full auctioning of allowances is a way of avoiding this process in a cap-and-trade system. Though full auctioning is rare, many cap-and-trade systems (e.g., the European Union Emissions Trading System) have partial auctions, with plans for the proportion of allowances auctioned to increase over time.

[7] For example, mobile sources (e.g. transportation) are often not covered under emissions trading systems.

emissions trading system. However, offsets are vulnerable to the same transactions cost issues that exist in any baseline-and-credit system, since the regulator has to evaluate and approve each individual project before granting the offsets. In fact, this evaluation and approval process can be particularly cumbersome in the case of offsets, since the project proponent must prove to the regulator that the emissions reductions associated with the project are in fact additional to what would have occurred in a business-as-usual scenario.[8] Depending on how complex, costly and time-consuming the entire approval process is, it may significantly reduce the additional cost savings from the offset system.

2.3 Emissions Trading in Practice

Before describing some of the cap-and-trade and intensity-based systems in practice today, it is worth noting some of the factors which have contributed to the rapid increase in interest in emissions trading, a trend which began in earnest in the U.S. in the late 1980s. Stavins (2003b) identifies a number of developments which combined to shift political attention towards emissions trading as an effective new approach to environmental policy. These include rising pollution control costs (prompting calls to find more cost-effective ways of achieving environmental goals), a growing acceptance of emissions trading in the environmental community[9], and a political shift in favour of using markets to solve social problems. In the debates at the time, economists also managed to successfully seperate the concepts of environmental targets from the environmental policy instruments used to achieve them. A view of emissions trading simply as a cost-minimizing instrument[10] made the concept more attractive to those who advocated lax targets as well as those pushing for more stringent ones.

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[8] This concept is often referred to as 'additionality'.

[9] A key component of this shift in perception was the recognition that the early emissions trading systems were more than just methods of reallocating abatement responsibility, but that they were also designed to reduce aggregate emissions.

[10] Tietenberg (2001) argues that early empirical cost-effectiveness studies (which showed that emissions trading could achieve targets at much lower costs than command-and-control regimes) were in fact a "pivotal point" in the move towards political acceptability of emissions trading.

One of the most important manifestations of the growing interest in (and political acceptance of) emissions trading was the launch of the U.S. national SO_2 cap-and-trade program (Carlson et al. 2000, Ellerman 2003, Burtraw and Palmer 2004).[11] The program was established through the 1990 U.S. Clean Air Act Amendments (CAAA) and targets SO_2 emissions, which are a key precursor to acid rain. The long term goal of the program was to reduce emissions of SO_2 from electricity-generating plants in the U.S. by nearly half of their 1980 levels by 2010. Phase I of the program ran from 1995 until 1999 and applied to relatively dirty coal-fired power plants. Phase II of the program began in 2000 and greatly expanded the number of regulated sources to include all generating units with more than 25 MW of capacity as well those using fuel with sulphur content above a certain level. The vast majority of allowances are grandfathered, though a small percentage (less than 3%) are allocated by means of a revenue-neutral auction.[12] Allowances from any year can also be banked for future use, and substantial banking did in fact occur during Phase I of the program. The overcompliance was partly due to the decline in rail rates which lowered the cost of low sulphur Powder River Basin coal, thereby lowering abatement costs. In addition, firms sought to bank permits in anticipation that the permit price would rise in Phase II as a result of the more stringent annual caps.

Although there is disagreement as to exactly how close the SO_2 allowance market has come to achieving its full potential in terms of efficiency (Burtraw et al. 2005), there is nonetheless evidence that

[11] Though it was by far the most significant emissions trading system to date, the SO_2 was not entirely unprecedented. The earliest experiments with emissions trading were undertaken by the U.S. EPA under the Clean Air Act, beginning in the mid-1970s. Initially, under the offset policy, new sources in areas where ambient air quality standards were violated were allowed to begin operations provided they ensured sufficient emissions reductions from existing sources. Later, other provisions (the bubble, banking and netting policies) were included that gave existing facilities the same flexibility, allowing them to exceed their regulated emissions levels so long as they ensured offsetting reductions on the part of other facilities in the same region. Collectively, these policies were codified by the EPA as the Emissions Trading Program (ETP) in 1986. It is important to point out that the ETP was not a standard cap-and-trade system, but rather a baseline-and-credit system. As described above, its status as a baseline-and-credit system contributed to high transactions costs and was an important factor in its mixed success (Hahn and Hester 1989).

[12] The format used in the U.S. program is similar to that proposed by Hahn and Noll (1983), except that buyers pay their actual bidding price, as opposed to a single market-clearing price.

substantial compliance cost savings were achieved as a result of trading and banking. For example, Carlson et al. (2000) estimate annual cost savings of roughly 43% ($784 million) during Phase II compared to a counterfactual policy of a uniform emissions intensity standard (with no trading). Ellerman et al. (2000) provide an even higher estimate of this figure, at 62% ($2.4 billion).[13] These cost savings, along with the continuing improvements in the performance of the allowance market and impressive environmental outcomes[14] (Ellerman 2003, Burtraw et al. 2005) have been key to the perception of the U.S. SO_2 cap-and-trade program as a success.

The 1990's also saw the launch of two regional cap-and-trade systems in the U.S. The greater Los Angeles area's Regional Clean Air Incentives Market (RECLAIM) was launched in 1994 (Harrison 2004). RECLAIM targets both SO_2 and NO_x emissions (the latter being a precursor to acid rain and tropospheric ozone or 'smog') from various industrial sources emitting more than four tons of either pollutant. Unlike the national SO_2 system, the RECLAIM program does not allow banking of allowances and separates the coastal and interior regions into two separate trading zones. It also features an offset provision, allowing participating firms to generate credits through projects that reduce emissions from mobile sources. Overall, experience with the RECLAIM program has been positive, though serious challenges emerged in 2000 when problems with the deregulation of California's electricity sector led to significant price spikes in the allowance markets.

The second regional cap-and-trade system, the OTC NO_x Budget Program, was launched in 1999 by nine states in the Northeastern U.S. (and the District of Columbia) in collaboration with the Ozone Transport Commission (OTC). The program was part of an overall strategy to reduce NO_x emissions in

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[13] Dollar values are in 1995 U.S. dollars. The discrepancy in estimates of dollar value cost savings between the studies is partly attributable to the differences in estimated counterfactual compliance costs. Carlson et al (2000) estimated total costs under command and control to be $1.82 billion, while Ellerman et al. (2000) placed this value at roughly $3.7 billion.

[14] For example, initial fears that allowance trading might lead to the creation of environmental 'hot spots' (areas of high concentrations of ambient pollution) have not materialized (Swift 2000).

the region. It operated for four years before being replaced by a geographically expanded program of similar design (and name): the NO_x Budget Trading Program (NBP). The new program, initiated by the EPA, includes several Eastern and Midwestern States in addition to the OTC states.[15] Notable features of the NBP are its provisions limiting the use of banked allowances[16], and its recognition of the seasonal nature of ozone formation: it operates only during summer months, thus focusing on emissions reductions when they are most beneficial.

Following the U.S.'s lead, other jurisdictions have implemented important emissions trading systems in recent years. In 2001, Ontario became the first Canadian province to implement a cap-and-trade system, targeting emissions of SO_2 and NO_x (Ontario MOE 2005). Though it was initially quite limited in scope, it was expanded in 2006 to include all major emitters in the electricity generation and industrial sectors. The system allows banking of allowances, and, like the RECLAIM program, incorporates offsets, allowing unregulated sources to generate credits through specific emission reduction projects. However, in contrast to most of the U.S. systems, allowances are distributed using an output-based allocation system such that a firm's share of total allowances for its industry is roughly proportional to its share of industry output. [17] Though Ontario's system may yet pave the road for others of its kind in Canada, it is still a relatively new system and a properly functioning market for allowances has been slow to develop. Whether it becomes a success and manages to achieve some of the anticipated cost savings remains to be seen.

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[15] In 1998, the EPA called on certain states to submit revised State Implementation Plans (SIPs) to outline how they planned to meet National Ambient Air Quality Standards for ozone and begin reducing emissions accordingly by 2004. The NBP was designed to help states meet these 'NO_x SIP call' obligations.

[16] When the total number of banked permits exceeds 10% of the annual allowance allocation, limits are imposed on the number of banked permits that can be used on a one-to-one basis. In other words, the banked permits are effectively discounted.

[17] To be accurate, allowance allocations in the U.S. systems *are* in fact based on activity levels (i.e. input or output levels) and a given emissions intensity rate, but they are based on activity levels during a particular historical period, such that current activity levels does not affect a firms' allocation. Also, Ontario actually has separate allocation schemes for the electricity generation and industrial sectors, but the results are similar.

No discussion of tradable permits would be complete without mentioning what is by far the largest and most well-known cap-and-trade system: the European Union Emissions Trading Scheme (EU ETS) for GHGs (Ellerman and Buchner 2007, Convery and Redmond 2007, Kruger et al. 2007, EC-EEA 2008, Ambrosi and Capoor 2008). Trading in the EU ETS began in 2005 as part of a three-year trial phase, and included all 25 EU member states at the time. Although it is independent of the Kyoto Protocol, the EU ETS was designed to help the EU meet its Kyoto obligations, and Phase II thus coincides with the Protocol's first five–year commitment period (2008-2012).[18] In addition, offsets acquired through Kyoto's Clean Development Mechanism or Joint Implementation provisions are admissible under the trading system.[19] This not only gives the system a 'global reach', but also provides firms with more flexibility in terms of compliance. This flexibility is further enhanced by provisions allowing banking and borrowing (against future allocations) of permits within each phase.

The EU ETS currently covers nearly 12,000 facilities in the energy production and industrial sectors, which collectively account for roughly half of EU's GHG emissions. Through the EU burden-sharing agreement, individual countries have been assigned national emissions caps totalling the EU-wide Kyoto target. Countries are responsible for determining how much of their national cap should be set aside for the sectors participating in the EU ETS as well as allocating permits to individual facilities.[20] Not surprisingly, both of these allocation processes have proven to be quite contentious in many cases.

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[18] The scheme has also been expanded for the second phase to include the two newest members of the EU (Romania and Bulgaria) as well as four non-EU countries (Norway, Iceland, Lichtenstein and Switzerland).

[19] Under the Kyoto Protocol, an Annex I country (i.e. one with emissions reduction obligations under the Protocol) can generate offsets which can be used to offset its own emission by funding emissions reduction projects in non-Annex I countries (under the Clean Development Mechanism) or other Annex I countries (under Joint Implementation).

[20] The remainder of the cap is then implicitly used to cover all remaining emissions sources (such as vehicles and other mobile sources), for which other policies aimed at encouraging abatement may be put in place.

The vast majority of permits have been freely distributed, though countries have the option of auctioning up to 10% of them during Phase II (as opposed to 5% in Phase I).[21]

The EU ETS market for permits has seen tremendous growth in trading activity since its inception and it has provided useful opportunities to gain insights into the challenges associated with linking and operating trading systems across multiple jurisdictions. This is of particular interest to those who envision the EU ETS as a first step towards a truly global GHG emissions trading system. Regardless of whether this development occurs anytime soon (or at all), it seems clear that the EU ETS will be a key component of any future global climate regime.

Thus far we've focused our discussion on cap-and-trade systems. While they remain the more popular approach to emissions trading, intensity-based systems have been attracting more attention recently. Proponents of intensity-based systems (and intensity targets in general) typically present arguments revolving around their compatibility with economic growth and competitiveness (Pizer 2005, Kuik and Mulder 2004). Firms in particular seem to prefer tradable performance standards to fixed targets for this reason, as experience with the U.K. Climate Change Agreements (CAA) demonstrates (UK DEFRA 2001, Smith and Swiersbinski 2007, Rosenzweig and Varilek 2003). The CAAs are agreements for emissions reductions between the government and various sectoral industry organizations, and form part of the U.K.'s 2000 Climate Change Programme (which was designed to ensure that the U.K. would meet its Kyoto commitments). The vast majority of these agreements (39 of 44) have set targets in terms of energy intensity of output (which is converted to an emissions intensity of output)[22] as opposed to absolute caps.

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[21] Few countries auctioned any permits during Phase I, and only one (Denmark) of these chose to auction the full allowable amount of 5%.

[22] In addition, one of the remaining five agreements (the agreement with the aluminum industry) was explicitly set in terms of emissions per unit of output.

Firms covered under CAAs now participate in an intensity-based trading system[23] which will run until 2010. For several years, the intensity-based system operated alongside the U.K.'s voluntary cap-and-trade system for GHGs (the UK ETS)[24]. Because of concerns that trading between the intensity-based system and the cap-and-trade system could undermine the latter system's fixed emissions targets, trading between the two systems was limited by the 'Gateway' mechanism. The mechanism only allowed trading so long as there was no positive net flow of allowances/credits from the CAA (intensity-based) sector to the cap-and-trade sector. The Gateway mechanism is a reflection of the unease about flexible intensity targets that is often displayed by environmental groups.

In 2005, the Netherlands launched a similar intensity-based system to the U.K.'s, only it was designed for NO_x emissions (NL VROM 2005). The Dutch NO_x trading system is part of a larger national policy designed to achieve reductions of NO_x emissions of nearly 50% relative to 1995 levels by the year 2010, in compliance with the EU directive on National Emission Ceilings (NEC Directive). Baseline emissions levels are determined according to a 'Performance Standard Rate' (PSR), which is measured in terms of emissions intensity of energy use for certain sources and emissions intensity of output for others. In all cases, the PSRs are made progressively more stringent each year.

In early 2008, Canada unveiled the details of its planned regulatory framework for industrial GHG emissions (Environment Canada 2008). Though the plan is presented as integral to meeting the current government's goal of reducing absolute levels of GHG emissions by 20% below 2006 levels by 2020, the regulations themselves revolve around intensity targets. Specifically, all covered sources will be required to reduce the emissions intensity of their production output by 18% below 2006 levels by 2010 and by a further 2% annually in subsequent years. In addition to trading credits, firms have access

[23] Firms that accepted absolute caps are referred to as "direct participants", referring to the fact that they are allocated allowances equal to their caps (as in a standard cap-and-trade system). Firms that accepted intensity targets are referred to as "agreement participants" and their participation is through a baseline-and-credit, intensity-based system (Smith and Swiersbinski 2007).

[24] The cap-and-trade system was incorporated into the EU ETS in 2006.

to a number of other compliance mechanisms. Offset provisions are available to firms, and they can also meet (declining) portions of their regulatory obligations by making pre-certified investments in abatement projects or by contributing to a centrally-administered ‘technology fund’ at (relatively low) fixed rates per ton of CO_2 equivalent.[25] This feature essentially places a cap on the price of traded credits. It remains to be seen whether this price cap is low enough to actually hinder or prevent the development of a functioning market for credits.

2.3 Trends and Lessons Learned

No single approach to emissions trading (or environmental policy) is appropriate in all cases. However, many valuable lessons have been learned about which design features seem to generally contribute to successful emissions trading systems. Three in particular stand out. First, it is very important for systems to have long (or better yet, indefinite) time horizons (Burtraw 2007).[26] This ensures a certain level of certainty about the future regulatory environment, making it easier for firms to make long-term investments in abatement equipment and technologies. Second, allowing firms to bank allowances can be extremely beneficial. Banking has encouraged early emissions reductions, provided flexibility in the timing of investments and dampened price fluctuations (Burtraw 2007, Ellerman et al. 2003). Third, the most successful systems are transparent and simple (ibid.). Specifically, this means the tradable units are clearly defined and trades are not subject to an unnecessarily complex approval process. It means that the allocation process is straightforward and does not disguise large and unfair transfers of wealth. It also means that the monitoring, enforcement and compliance processes are uncomplicated and effective. The issue of simplicity and transparency is one of the reasons why the U.S. SO_2 system is

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[25] The rate is \$15/tonne of CO_2 equivalent from 2010 to 2013, and \$20 in 2013. In each subsequent year, the rate would increase at the nominal GDP growth rate. The fund will apparently be used to subsidize the development of emissions abatement technologies and emissions abatement projects.

[26] Burtraw criticizes the EU ETS for its short first (trial) phase, as firms faced a great deal of uncertainty about exactly how the system would operate in the second phase.

generally viewed much more positively than the EU ETS, which suffers from "unfortunate complexity" (Burtraw 2007, 15).

Abstracting from specific lessons about instrument design, we can also draw insights about broad trends in the choice between cap-and-trade systems and intensity-based systems, which of course reflects an even more fundamental choice between using absolute or intensity caps. The first thing to note is that absolute caps seem to dominate the policy landscape. There may be several reasons for this, including unease about the uncertainty of emissions levels (and thus environmental outcomes) with intensity caps. It may also be related to the perceived advantages of cap-and-trade systems in terms of simplicity. Nevertheless, our three examples of recently implemented intensity-based systems indicate that policy-makers are at least giving intensity caps more consideration. This is particularly true when it comes to climate change. For one, there seems to be growing recognition that greenhouse gases are a very good candidate for the use of intensity caps, since the impact on damages from variations in the absolute level of emissions in any given year is small.[27] In addition, policy makers are attracted to the flexibility of intensity caps, recognizing that this flexibility can greatly reduce the costs of achieving GHG emissions reductions (Gielen et al. 2002). Developing countries may be especially receptive to intensity caps for this reason, as they have thus far been unwilling to accept absolute caps on the basis that they place effective limits on economic growth (Pizer 2003). It may well be that if developing countries are to accept any limits on their greenhouse gas emissions, they will be in the form of intensity caps.

Many governments are in the process of seeking new methods of regulating air emissions, and the debate between absolute and intensity caps (and by extension, cap-and-trade and intensity-based systems) will continue to be an important one. This section has presented a survey of existing emissions trading systems, some key lessons that have been learned about their implementation, and identified some broad

[27] The link between emissions at a given point in time and environmental damages is very weak in the case of greenhouse gases, which are predominantly long-lived stock pollutants. Damages result (indirectly) from temperature increases, which are related to the stock of greenhouse gases in the atmosphere, which is in turn affected only marginally by emissions in a given year.

trends with respect to the use of absolute caps and intensity caps. The next section will approach the absolute vs. intensity cap debate from a theoretical perspective, by presenting an overview of the literature comparing the two.

3 Literature Review

There are two key branches of the literature devoted to analysing absolute and intensity caps in a comparative context. The first addresses the issue under conditions of certainty, and is focused primarily on the instrument choice problem (i.e. comparing cap-and-trade and intensity-based systems). The second is concerned with the relative performance of absolute and intensity caps targets in the presence of uncertainty about future realized GDP levels, emissions intensity of GDP, BaU emissions levels[28] (and by extension of these, abatement levels), and the schedule for marginal costs of abatement. Analyses in this area are principally concerned with economy-wide targets for GHGs, abstracting from firm-level incentives and behaviour. This section will provide overviews of each of the two branches in turn. It will conclude with a more detailed discussion of Quirion's (2005) paper, with the goal of presenting the basic motivation for the extension of his model which is developed in section 4.

3.1 Absolute vs. Intensity Caps under Certainty

The branch of literature focused on comparing absolute and intensity caps under certainty makes several important assumptions. Most importantly, market demand and production (and abatement) costs are assumed to be known. In this context, the focus of the analyses is on the impacts of absolute and intensity caps on micro-level abatement and production incentives. The two most important results of this literature are that both absolute and intensity caps are capable (through the use of cap-and-trade and intensity-based systems, respectively) of inducing equalized marginal costs of abatement across firms and that intensity caps provide an inefficient output subsidy to firms.

[28] Of course, GDP levels, emissions intensity of GDP and emissions levels are each determined by the other two according to a simple identity (intensity=emissions/GDP), such that uncertainty about any one of the three can be expressed in terms of uncertainty with the respect to the other two.

Fisher (2003a) presents a simple comparative analysis of absolute and intensity caps under conditions of certainty. Her partial equilibrium model involves two (perfectly competitive) industries, each with a representative firm. One industry is subject to an absolute emissions cap (through the use of a cap-and-trade system) and the other is subject to an intensity cap (through the use of an intensity-based system). In each industry, total emissions (E_i) are the product of total output (Q_i) and the emissions intensity rate (μ_i), so that $\mu_i = \frac{E_i}{Q_i}$. Marginal production costs are a function only of the intensity rate, and are represented by $c(\mu)$. Marginal production costs are the same in both industries[29] and are decreasing in the intensity rate, provided $\mu < \mu_i^0$, where μ_i^0 is some natural emissions rate. Thus, we have that $c(\mu) > 0$, $c'(\mu) \leq 0$, $c''(\mu) > 0$ and $c'(\mu_i^0) = 0$. Demand is identical in both industries, and is a declining function of the product price: $Q(P_i)$.

For the industry subject to the cap-and-trade system, total emissions are capped at $\bar{E}$, and each firm is given an initial allocation of $\bar{A}$ permits. For the representative firm, profits are revenues less the sum of production costs and net permit purchases:

$$\pi_1 = Q_1(P_1 - c(\mu_1) - t_1\mu_1) + t_1\bar{A} \tag{a}$$

where P_1 is the sector's product price, and t_1 is the market price of permits. The profit-maximizing firm will choose the optimal emissions intensity rate μ_1^* such that the marginal cost of abatement is equal to the marginal price of emissions (i.e. the permit price).

$$-c'(\mu_1^*) = t_1 \tag{b}$$

In the competitive industry equilibrium, the product price is the sum of marginal production costs and permit costs,

$$P_1^* = c(\mu_1^*) + t_1\mu_1^* \tag{c}$$

and the permit price is such that the absolute cap binds ($\bar{E} = \mu_1^* Q_1^*$) and (b) and (c) hold.

[29] The simplifying assumptions that production costs and demand are the same in both sectors is our own, and does not affect the basic results presented here. Fischer's model allows for different production costs and demand functions in the two industries.

For the industry subject to the intensity-based system, the industry-wide emissions intensity rate is fixed at $\bar{\mu}$. Firms which produce with intensity rates below $\bar{\mu}$ generate permits which they can sell to firms which produce with intensity rates above $\bar{\mu}$. As discussed in Section 2, a firm's baseline allowable level of emissions is a function of output. So firms that choose to produce with an intensity rate below the baseline ($\mu_2 < \bar{\mu}$) receive an amount equal to $t_2(\bar{\mu} - \mu_2)Q_2$, while those that produce with an intensity rate above the baseline ($\mu_2 > \bar{\mu}$) must pay an amount equal to $t_2(\mu_2 - \bar{\mu})Q_2$. Notice that an equivalent situation would be if firms were forced to pay for the full cost of their emissions ($t_2\mu_2Q_2$) but were also given an output subsidy of $t_2\bar{\mu}Q_2$. Thus, for the representative firm, profits are equal to the sum of total revenues and the implicit output subsidy, less the sum of production costs and emissions costs:

$$\pi_2 = Q_2(P_2 - c(\mu_2) - t_2(\mu_2 - \bar{\mu})) \tag{d}$$

As with the cap-and-trade system, the profit maximization requires that the firm choose the optimal emissions intensity rate μ_2^* such that the marginal cost of abatement is equal to the marginal price of emissions (i.e. the permit price).

$$-c'(\mu_2^*) = t_2 \tag{e}$$

The equilibrium product price is the sum of marginal production costs and permit costs net of the implicit subsidy:

$$P_2^* = c(\mu_2^*) + t_2(\mu_2^* - \bar{\mu}) \tag{f}$$

Given that for the industry as a whole, the intensity rate must be $\bar{\mu}$, (f) simplifies to

$$P_2^* = c(\bar{\mu}) \tag{f'}$$

The first thing to note is that, from (b) and (e), we have that both the cap-and-trade system and the intensity-based system will result in equalized marginal abatement costs across firms. In other words, there will be an efficient allocation of abatement responsibilities. However, this does not imply that both approaches are equally efficient methods of achieving a given environmental target. Take the case where both systems induce the same intensity rate ($\bar{\mu} = \mu_1^*$) and by extension, the same marginal abatement cost ($t_1 = t_2 = -c'(\bar{\mu})$). From (c) and (f'), we have that $P_1^* = c(\bar{\mu}) + t_1 \bar{\mu} > c(\bar{\mu}) = P_2^*$. The lower price in the industry with the intensity-based system is the result of higher output. This in turn implies that emissions in the industry covered by the intensity-based system will be higher than emissions in the cap-and-trade industry: $E_1 = \bar{\mu}Q(P_1) < \bar{\mu}Q(P_2) = E_2$. Because of the implicit output subsidy, an intensity-based system will result in higher emissions levels compared to a cap-and-trade system with the same marginal abatement cost. It follows that achieving a given level of emissions requires higher abatement costs with an intensity-based system, since abatement choices are distorted to favour emissions *intensity* reductions at the expense of output contraction. In fact, while a cap-and-trade system[30] can induce the optimal level of emissions, output (and correspondingly, output price) and marginal cost of abatement, an intensity-based system can only induce one of the three at any time. Several other authors have criticized intensity-based systems on the basis of their implicit output subsidy, including Helfand (1991), Muller (1999), Dewees (2001) and Gielen et al. (2002). [31]

3.2 Absolute vs. Intensity Caps under Uncertainty

Another branch of the literature approaches the comparison between absolute and intensity caps from a very different angle. The analyses focus on the performance of each type of cap when there is uncertainty about crucial factors such as future GDP levels, emissions intensity of GDP, BaU emissions

[30] An emissions tax can also achieve the same described outcome as a cap-and-trade system.

[31] A common assumption made in these analyses is that of perfect competition in output markets. However, under the assumption of imperfect competition, when output levels are sub-optimal, such an output subsidy may be desirable. Fischer (2001, 2003b) acknowledges that the output support of a tradable performance standard may improve its relative performance under imperfect competition, just as it may alleviate the problem of emissions 'leaking' to unregulated producers outside of the program (see also Gielen et al. 2002). However, she points out that in such cases, it will always be more efficient to separate regulations aimed at correcting environmental externalities and those addressing market structure or the relative competitiveness of certain sectors.

levels (and by extension of these, abatement levels), and marginal abatement cost schedules. Crucially, they ignore the output subsidy aspect of intensity caps, as they are examining fundamentally different questions than the literature described above. One component of the 'uncertainty literature' is composed of analyses that have pointed to the considerable uncertainty about the costs of meeting absolute emissions caps, and investigate the potential of intensity caps to reduce this uncertainty. The models are typically macro-level, dynamic empirical models which are focused on greenhouse gas emissions. Some even explicitly account for the fact that greenhouse gases are stock pollutants (as opposed to flow pollutants). A second component of the uncertainty literature compares the welfare implications of the different types of caps, and uses microeconomic models which are static and more reasonably applicable to flow pollutants. This subsection will address both of these components of the uncertainty literature in turn.

Kim and Baumert (2002) and Strachan (2003) are among the authors who strongly support the use of intensity caps for greenhouse gases as a means of reducing abatement cost uncertainty. Kim and Baumert propose a 'dual-intensity target' for international climate change agreements, which would theoretically provide greater flexibility than a standard intensity cap. The dual-intensity target essentially involves a *range* of intensity levels. A country whose realized emissions intensity falls within this range would be considered to be meeting its commitments, and no sale or purchase of emissions credits would be necessary. Strachan (2003) uses historical U.S. data to analyse trends and determinants of the baseline CO_2 emissions levels, and, finding that actual emissions levels exhibit much higher variance than emissions intensity, lends his support to the use of projected emissions intensity as the baseline metric against which (intensity) reduction targets are set.

Sue Wing et al. (2006) take a different modelling approach. They treat future GDP and future BaU emissions as uncertain and compare the performance of intensity and absolute emissions caps according to two criteria. The first judges the caps on the basis of how well they minimize the difference between the resulting (absolute) level of abatement and the initially-expected level. The second focuses on minimizing the variance of abatement through time. Interestingly, they find that with respect to both criteria, the intensity cap outperforms the absolute cap whenever the variance of GDP is not too large relative to that of emissions levels and the correlation between GDP and emissions levels is sufficiently high. They also find that the degree of abatement being undertaken can affect the choice of cap, with intensity caps being preferred for more aggressive abatement policies and absolute caps being preferred when only moderate abatement is desired. Another key result draws upon earlier work (Ellerman and Sue Wing 2003), and states that a partial intensity cap (i.e. a weighted average of an absolute cap and intensity cap) will always dominate an absolute cap when the weights are set optimally. Finally, they use data from eleven countries to test their results, finding that the case for intensity caps is very strong for developing countries, while the choice between an absolute and intensity cap may be more ambiguous for developed countries.

Some of the key results found by Sue Wing et al. (2006) are confirmed by Marschinski and Lecocq (2006)[32], albeit with important qualifications. Their approach differs most notably by the fact that they explicitly model uncertainty about abatement costs (as opposed to just level of abatement). In addition, they examine the relative performance of the two instruments in terms of the variance of *general* abatement effort (a combination of absolute and relative abatement[33]), marginal abatement costs and total costs relative to GDP. They develop explicit conditions for the dominance of one instrument over the other, and also find that a general intensity cap[34] can be designed such that uncertainty is always lower than under an absolute cap (except in the case of total costs relative to GDP). Testing their model empirically, Marschinski and Lecocq are (unlike Sue Wing et al.) fairly pessimistic about intensity caps

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[32] Specifically, they also find that higher degrees of correlation between GDP and emissions and similar variances for GDP and emissions tend to favour intensity targets, as do more ambitious abatement regimes

[33] Relative abatement refers to the percentage reduction in emissions relative to BaU levels, while absolute abatement refers to the actual amount of emissions reduced.

[34] Their 'general intensity target' (which we term a 'cap' for consistency) is a power-law function of GDP.

on uncertainty grounds, finding that for most of the range of plausible parameter values, an absolute cap is preferable. Moreover, they find that in most cases, the optimal partial intensity cap is much closer to an absolute cap than a standard (i.e. linear) intensity cap.

Jotzo and Pezzey (2007) develop a model of a single-period, multi-country emissions trading regime under risk aversion and uncertainty about GDP and BaU emissions intensity in the 'linked' portion of the economy and BaU emissions not linked to GDP. Their results further confirm that an optimally calibrated general intensity cap will always dominate an absolute cap. They also find that greater GDP uncertainty, degrees of risk aversion and degrees of linkage between GDP and emissions contribute to the performance of a standard intensity cap (relative to an absolute cap) and, by extension, the degree of indexation associated with the optimal general intensity cap. Their empirical results present a strong case for intensity caps, except for particular developing countries. This result is quite interesting and stands in contrast to the rest of the literature in this area. It appears as though greater risk aversion and GDP uncertainty for developing countries is dominated by the fact that their 'energy sectors'[35] (which are presumed to be linked to GDP) make up smaller shares of their total emissions, compared to most industrialized countries.

As part of the second component of the literature on absolute and intensity caps under uncertainty, Quirion's (2005) paper is an important departure from those described above. Quirion follows Weitzman's (1974) approach of comparing the *welfare* implications of pollution control instruments when there is uncertainty with respect to marginal abatement costs. Weitzman's fundamental insight was that a price instrument (such as an emissions tax or abatement subsidy) will be preferred to an absolute emissions cap whenever the slope of the marginal abatement cost curve exceeds that of the marginal damage curve. Conversely, relatively flat marginal abatement costs favour absolute emissions caps. The basic intuition for this result is fairly straightforward. An emissions tax will lead firms to

[35] Energy sectors are basically defined as sectors with high levels of fossil-fuel combustion.

reduce their emissions until their marginal cost of abatement is just equal to the amount of the tax. Thus, a tax fixes marginal abatement costs and allows actual emissions to fluctuate. An absolute cap on emissions does just the opposite, fixing the level of emissions while allowing the marginal cost of abatement (i.e. the price of emissions permits) to fluctuate. Although abatement costs will always be minimized with a price instrument, it is very difficult to control emissions levels and hence damage costs. The flatter the marginal abatement cost curve, the more difficult it is to control emissions and the steeper is the marginal damage curve, the higher the damage costs incurred from this lack of emissions quantity control.

Weitzman's insights on the performance of otherwise equivalent price and quantity instruments under uncertainty have provided the basis for fundamental contributions to the debate about climate change policy. Pizer (2002) uses an integrated climate-economy model to demonstrate that a price instrument would be far more efficient (by a factor of five to one) than an absolute emissions cap for regulating emissions of greenhouse gases under uncertainty about abatement costs. The result is attributed to the fact that marginal damages from emissions of greenhouse gases are essentially flat: emissions in a given year are fairly insignificant relative to the accumulated stock of greenhouse gases which is the cause of climate change and its associated damage costs. At the same time, marginal abatement costs are assumed to be relatively steep for the relevant range of abatement effort.

Pizer's basic case in favour of price instruments for regulating greenhouse gases is supported by Newell and Pizer (2003). They develop a model of policy choice for regulating the externality associated with a stock pollutant under uncertainty. Their key result demonstrates that while the relative slopes of the marginal damage and marginal abatement cost curves play a crucial role in choosing between price and quantity instruments, stock decay rates, discount rates and correlation in costs across time are also important. Armed with a model that more accurately accounts for the fact that greenhouse gases are stock pollutants, Newell and Pizer examine the case of climate change and again find that a price instrument dominates an absolute emissions cap (yielding net benefits that are as much as five times greater).

Quirion's model is also inspired by Weitzman's. Quirion compares the welfare implications of a price instrument (*P*), an absolute cap (*Q*) *and* an intensity cap (*I*), under the assumption of linear marginal abatement cost (MAC) and emissions environmental damage (MED) curves. Uncertainty is assumed to exist with respect to BaU emissions[36] as well as the slope of the MAC curve. A key assumption that Quirion makes (departing from Weitzman) is that abatement costs are a function of *relative* abatement. Quirion finds that an intensity cap will dominate an absolute cap whenever the expected MAC curve is steeper than the marginal damage curve. This is of course the same condition for which Weitzman found price instruments (i.e. taxes) to be preferable to absolute caps. However, when comparing price instruments to intensity caps, Quirion finds that the latter is only preferable in the unlikely case when the slope of the marginal damage curve does not significantly exceed that of the MAC curve *and* there are high levels of uncertainty with regards to BaU emissions. Thus, Quirion's model leads him to conclude that an intensity cap will only be the preferred instrument for a fairly small range of key parameter values, and that an absolute cap will still dominate whenever the marginal damage curve is steeper than the MAC curve.

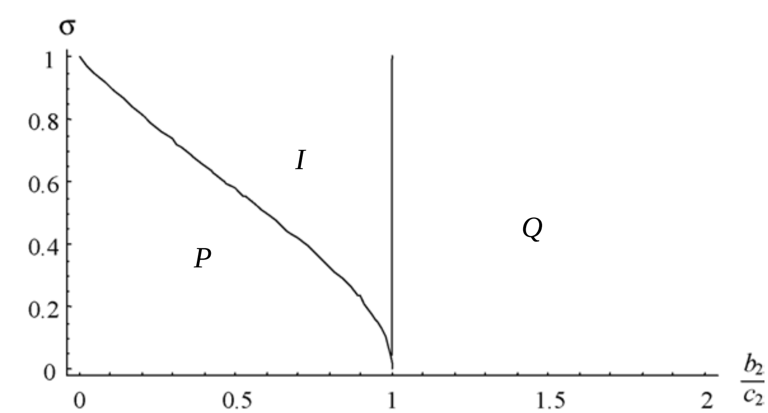

Figure 1. Preferred instrument in the parameter space. $\boldsymbol{\sigma}$ is the standard deviation of the BaU emissions level, $\boldsymbol{b_2}$ is the slope of the marginal emissions damage curve and $\boldsymbol{c_2}$ is the expected slope of the marginal abatement cost curve. Source: Quirion 2005.

[36]Quirion assumes that emissions and output are perfectly linked and normalizes the associated parameter such that it equals 1 in expectation. In this setting, the intensity cap is effectively indexed to BaU emissions.

A closer look at Quirion's model and its assumptions reveals an interesting intuitive explanation for his results. Specifically, one of his propositions ('Proposition 1') is that when there is only uncertainty with regards to BaU emissions (i.e. uncertainty with regards to the slope of the MAC curve is eliminated)[37], the intensity cap and the price instrument are equivalent. They both serve to fix marginal abatement costs. In the case of the intensity cap, this is a result of Quirion's assumptions that output and BaU emissions are perfectly linked and that marginal abatement cost is a function of *relative* abatement. The first assumption ensures that the intensity cap fixes the level of allowable emissions, and thus abatement, as a proportion of BaU emissions (as opposed to just as a proportion of output). With relative abatement held constant in this way, the second assumption implies that the marginal abatement cost will also be held constant. Thus, there is a clear link between Quirion's assumption that marginal abatement cost is a function of relative abatement, and the essential similarity he observes between the intensity cap and the price instrument.

Proposition 1 is displayed graphically in Figure 2, which shows the outcomes of the three instruments when there is only uncertainty with respect to BaU emissions (α). As drawn, BaU emissions are higher than expected. $\bar{p}$ and $e(\bar{p})$ are the optimal price level of the price instrument and the resulting emissions level, respectively; $\bar{e}$ and $p(\bar{e})$ are the optimal absolute emissions cap and resulting price, respectively; $e(\bar{r})$and $p(\bar{r})$ are the emissions level and price under the optimal intensity cap, respectively; and $e^*$and p^* are the ex post optimal emissions levels and price, respectively. Notice that the price instrument and intensity cap yield the same emissions and price levels, and thus result in the same social loss relative to the ex post optimum (which is defined by the intersection of the MAC curve and the MED curve).

[37] Note that, in Quirion's model, changes in BaU emissions still lead to changes in the slope of the MAC curve, albeit indirectly. The key distinction is that changes in BaU emissions lead to changes in the horizontal (emissions) intercept of the MAC curve, while 'direct' changes in its slope lead to changes in the vertical (price) intercept of the MAC curve.

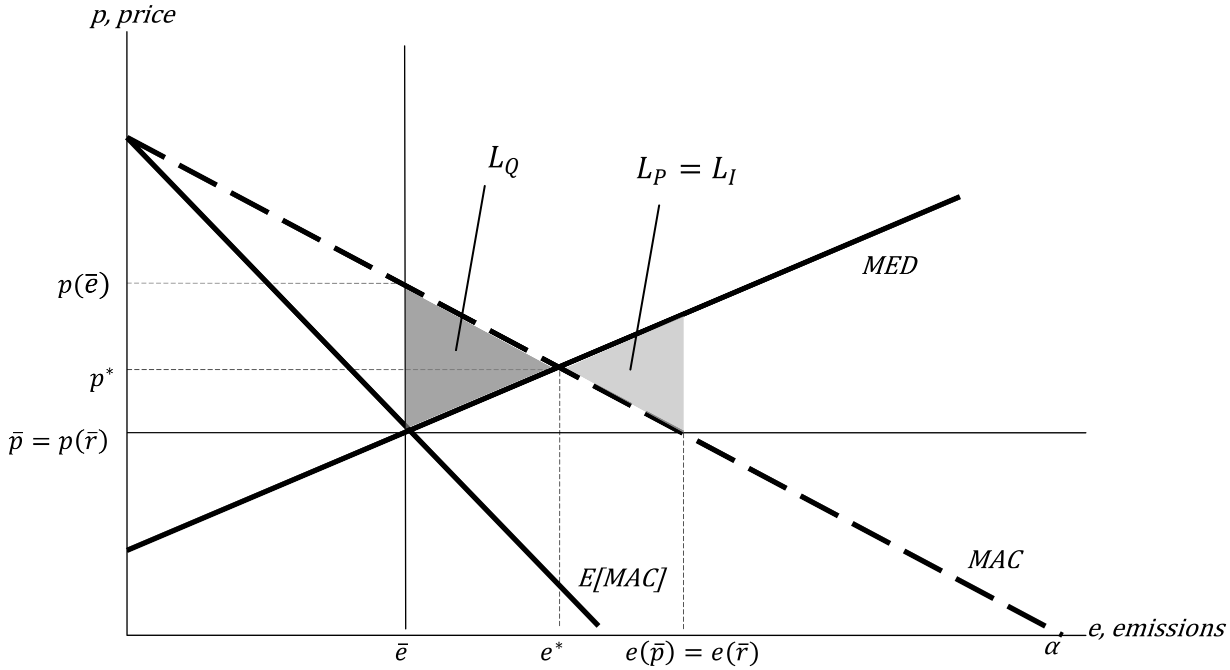

Figure 2. Uncertainty about BaU emissions. With higher than expected BaU emissions (the emissions intercept of the MAC curve), the emission level is too high under the intensity cap and the price instrument (which are equivalent in this case), and too low under the absolute cap, relative to the ex post optimum. $\boldsymbol{L_i}$ represents the resulting social loss under instrument *i*.

Consider another of Quirion's propositions ('Proposition 2') – that the intensity cap and absolute cap are equivalent when there is only uncertainty with respect to the slope of the MAC curve (i.e. when uncertainty with regards to BaU emissions is eliminated). Proposition 2 is displayed in Figure 3, which shows that in this setting both the intensity cap and absolute cap serve to fix the level of allowable emissions.[38] The obvious implication of Proposition 2 is that the differences in the relative performance of the intensity cap and the absolute cap are based solely on uncertainty with respect to BaU emissions.

[38] This is true in the case of the intensity target because changes in allowable emissions only come from changes in BaU emissions. Recall the simple mathematical identity: emissions = (intensity rate) x (output). In Quirion's model, as mentioned, output and BaU emissions are assumed perfectly linked and represented by the same variable, such that this identity can be written as: emissions= (intensity rate) x (BaU emissions). In addition, the optimal intensity rate itself is not affected by uncertainty with regards to the slope of the marginal abatement cost curve.

Now, recall the equivalence between the intensity cap and price instrument when there is only uncertainty with respect to BaU emissions (from Proposition 1). Combining these two insights, it is perhaps not very surprising that Quirion finds that the criteria for choosing between an intensity cap and an absolute cap is essentially the same as Weitzman's criterion for choosing between a price instrument and an absolute cap. It seems reasonable to presume that it is precisely because of the intensity cap's similarity to a price instrument that they are both preferred to an absolute cap according to the same criterion (i.e. whenever the MAC curve is steeper than the marginal damage curve). Recalling the importance to Proposition 1 of Quirion's assumption about relative abatement determining marginal abatement cost and the equivalence of the intensity cap and price instrument, we find that there is a fairly strong logical connection between this assumption and his findings concerning the relative performance of the intensity cap and absolute cap.

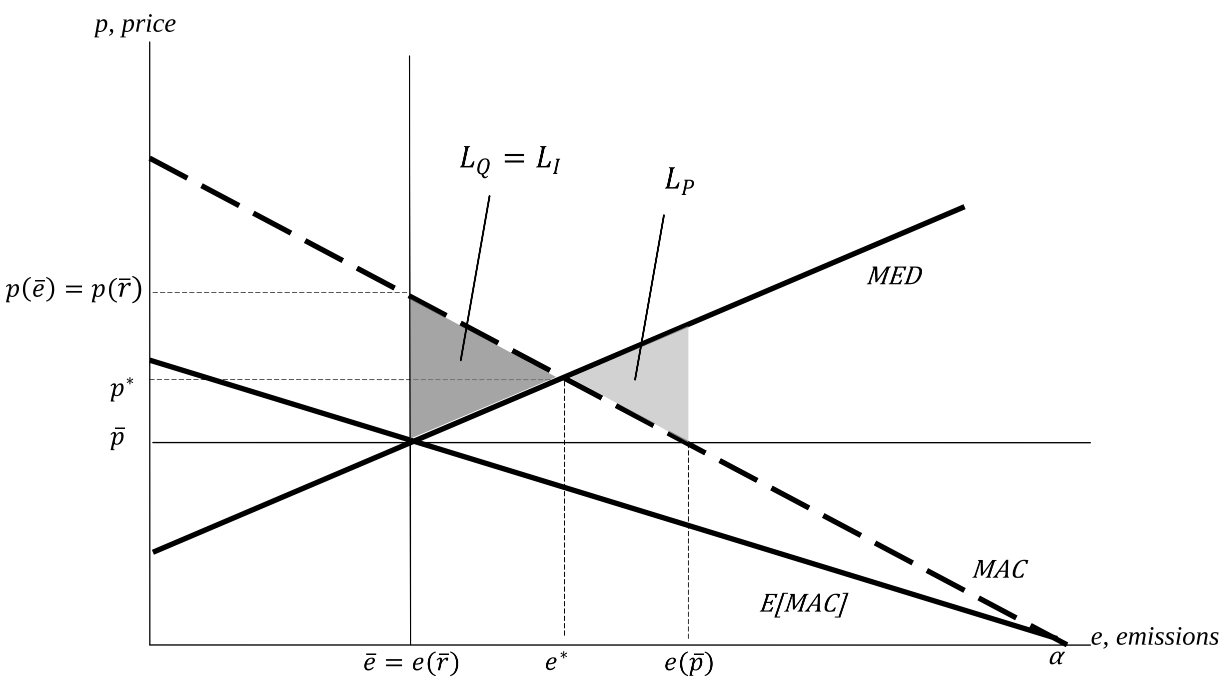

Figure 3. Uncertainty about the slope of the MAC curve. With a higher than expected slope (price intercept) of the MAC curve, the emission level is too low under the intensity and absolute caps (which are equivalent in this case), and too high under the price instrument, relative to the ex post optimum. $\boldsymbol{L_i}$ represents the resulting social loss under instrument *i*.

Given the above analysis, an interesting question to explore is whether different conditions for the dominance of an intensity cap over an absolute cap would emerge in a setting where the argument of the abatement cost function is absolute abatement, as opposed to relative abatement.[39] This is the focus of the remainder of the paper, in which Quirion's model will be modified and extended to examine the implications of assuming abatement cost as a function of absolute abatement.

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[39] Moreover, it is likely that in certain cases absolute abatement is a more appropriate measure of abatement effort. An interesting (albeit extreme) example is provided by Marschinksi and Lecocq (2006): that of 'offsetting' carbon dioxide emissions using forest carbon sequestration (i.e. reforestation). In this case, abatement costs would depend primarily on the number of trees planted (and by extension, the tons of carbon sequestered), not how much of a proportional reduction in BaU emissions this would represent. For the economy as a whole, it is most likely that neither absolute nor relative abatement is entirely appropriate, and abatement costs would be a function of some combination of the two (Ibid.).

4 The Model

The model presented in this section is an extension of the model developed by Quirion (2005) to compare the performance (in terms of welfare) of an intensity cap to an absolute cap and to a price instrument, when there is uncertainty with regards to abatement costs. We depart from Quirion's model in two fundamental ways. Most importantly, we assume marginal abatement cost to be a function of the absolute amount of emissions reduced, as opposed to the percentage reduction in emissions relative to BaU levels. In addition, we consider only one type of cost uncertainty – uncertainty with respect to BaU emissions levels. Thus, we consider uncertainty with respect to the position of the marginal abatement cost curve (as in Weitzman (1974)), but not its slope.

4.1 Abatement Costs and Environmental Damages

4.1.1 Abatement Costs

In order to derive our abatement cost function, we begin by specifying an emissions benefit function[40]:

$$B(e) = \alpha a_2 e - \frac{a_2}{2} e^2 \tag{1}$$

where $e \in [0, \alpha]$ represents the level of emissions, α represents both ex post BaU emissions and production level (which are assumed to be exogenous), and $a_2 > 0$. Following Quirion, we characterize α as a stochastic variable which is normalized such that $E[\alpha] = 1$ and $E[\alpha^2] = 1 + \sigma^2$, where σ^2 is the variance of α.

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[40] If we assume that production costs are falling with emissions at the firm level, then emissions benefits can be thought of in terms of reduced production costs.

In order to better understand the emissions benefit function, it is useful to depict it strictly as a function of BaU emissions: $B(\alpha) = A\alpha - \frac{a_2}{2}\alpha^2$, where A is a stochastic variable. Taking the first order condition with respect to α yields $A = \alpha a_2$. Substituting $A = \alpha a_2$ into $B(\alpha)$ yields (1). Thus, α is a stochastic variable because A is a stochastic variable.

The marginal benefit of a unit of emissions is given by:

$$B'(e) = \alpha a_2 - a_2 e \tag{2}$$

Maximizing (1) with respect to e demonstrates that benefits are maximized when emissions are at the BaU (unregulated) level (i.e. when $e = \alpha$). Therefore, we can define total abatement costs as the difference between maximized benefits and benefits when $e < \alpha$:

$$TAC = B(\alpha) - B(e) = a_2\alpha^2 - \frac{a_2}{2}\alpha^2 - (\alpha a_2 e - \frac{a_2}{2}e^2)$$

$$TAC = \frac{a_2(\alpha - e)^2}{2} \tag{3}$$

Marginal abatement costs are:

$$MAC = \alpha a_2 - a_2 e \tag{4}$$

These can be compared to the total abatement cost and associated marginal abatement cost functions used in Quirion's model:

$$TAC = \frac{a_2(\alpha - e)^2}{2\alpha} \tag{5}$$

$$MAC = a_2 - \frac{a_2}{\alpha}e \tag{6}$$

Notice that in Quirion's model, uncertainty in BaU emissions translates into uncertainty about the location *and* the slope of the MAC curve. More specifically, increases (decreases) in α will decrease (increase) the slope of the MAC curve ($\frac{a_2}{\alpha}$) but leave the marginal cost of full abatement unaffected,[41] such that changes in α rotate the MAC curve. In our model, uncertainty in BaU emissions translates into uncertainty about the location of the MAC curve, while the slope of the curve (a_2) remains fixed. Increases and decreases in α translate into horizontal shifts of the MAC curve.

[41] In order to model uncertainty with respect to the slope of the MAC curve, Quirion treats a_2 as a stochastic variable. In contrast, A (defined in footnote 40) is a stochastic variable in our model, where increases (decreases) in A shift the MAC curve up (down), but do not affect its slope.

4.1.2 Environmental Damages

We follow Quirion's approach to modeling the externality costs associated with emissions.[42] Thus, total environmental damages are given by

$$TED = b_1 e + b_2 \frac{e^2}{2} \tag{7}$$

so that marginal environmental damages are

$$MED = b_1 + b_2 e \tag{8}$$

where $MED(0) = 0$, $MED(e) > 0$, $0 \leq b_1 \leq a_2$, and $b_2 \geq 0$ such that the optimal emissions level is nonnegative.[43] Notice that while we assume marginal damages to be increasing in emissions level, we do not assume any specific threshold level of emissions beyond which damages increase dramatically.[44]

4.2 Optimal Instrument Design under Uncertainty

Using our expressions for abatement costs and environmental damages, (3)and (7), we can define total social cost as their sum:

$$TSC = TAC + TED = \frac{a_2(\alpha - e)^2}{2} + b_1 e + b_2 \frac{e^2}{2}$$

Rearranging this expression yields

$$TSC = \frac{a_2}{2}\alpha^2 + (b_1 - a_2\alpha)e + (\frac{a_2 + b_2}{2})e^2 \tag{9}$$

For each of the three instruments (an absolute emissions cap, an intensity cap and a price instrument) the regulator chooses the associated policy parameter so as to minimize the expected value of TSC (9).

[42] This includes omitting uncertainty with respect to the damage function, since, as Quirion notes, it has been shown that this uncertainty does not affect the ranking of instruments, unless damage uncertainty is correlated with abatement cost uncertainty (Stavins 1996).

[43] In order to ensure that the ex post optimal emissions level is *always* nonnegative, it must be that $b_1 \leq a_2\alpha$, which would require that α follow a distribution with a lower bound of $\frac{b_1}{a_2}$. Though this more strict condition will be imposed in the sections 4.4 and 4.5, it is not required in order to prove any of our basic results.

[44] For example, such a damage curve would be appropriate for specific cases where pollution levels beyond a certain threshold imply the extinction of a key species or the collapse of an ecosystem.

4.2.1 Absolute Emissions Cap/Quota (Q)

With an absolute emissions cap (as in a cap-and-trade system), the regulator chooses the level of allowable emissions that minimizes the expected value of TSC (9). Thus, the optimal cap $\bar{e}$ is found by solving the following:

$$\min_{\bar{e}} \ E[TSC(Q)] = E\left[\frac{a_2}{2}\alpha^2 + (b_1 - a_2\alpha)e + \left(\frac{a_2 + b_2}{2}\right)e^2\right]$$

$$= \frac{a_2}{2}(1 + \sigma^2) + (b_1 - a_2)e + \left(\frac{a_2 + b_2}{2}\right)e^2 \tag{10}$$

Taking the first order condition, we find

$$\bar{e} = \frac{a_2 - b_1}{a_2 + b_2} \tag{11}$$

We can determine the resulting price of emissions permits, which is the MAC evaluated at $\bar{e}$. Thus, from (4) and (11):

$$p(\bar{e}, \alpha) = a_2\alpha - a_2\left(\frac{a_2 - b_1}{a_2 + b_2}\right) \tag{12}$$

4.2.2 Intensity Cap (I)

With an intensity cap, the regulator fixes the emissions to output ratio r, such that the resulting level of emissions is

$$e = r\alpha \tag{13}$$

Thus, the regulator's social cost minimization problem is (from (13) and TSC (9)):

$$\min_{r} \ E[TSC(I)] = E\left[\frac{a_2}{2}\alpha^2 + (b_1 - a_2\alpha)(r\alpha) + \left(\frac{a_2 + b_2}{2}\right)(r\alpha)^2\right]$$

which can be manipulated to yield

$$\min_{r} \ E[TSC(I)] = \frac{a_2}{2}(1 + \sigma^2) + (b_1 - a_2)r + \left(\frac{a_2 + b_2}{2}\right)r^2 + \sigma^2\left(-a_2 r + \left(\frac{a_2 + b_2}{2}\right)r^2\right) \tag{14}$$

Taking the first order condition, we find the optimal intensity rate

$$\bar{r} = \frac{a_2(1 + \sigma^2) - b_1}{(a_2 + b_2)(1 + \sigma^2)} \tag{15}$$

which can be written in terms of the optimal absolute cap:

$$\bar{r} = \bar{e} + \left(\frac{\sigma^2}{1+\sigma^2}\right)\left(\frac{b_1}{a_2+b_2}\right) \tag{15`}$$

Since $0 \leq b_1 \leq a_2$ and $b_2 \geq 0$, the optimal intensity rate, $\bar{r}$, is bounded as follows[45]:

$$\frac{a_2\sigma^2}{(a_2+b_2)(1+\sigma^2)} \leq \bar{r} \leq \frac{a_2}{a_2+b_2} < 1 \tag{16}$$

From (15) and (16), we can identify the limiting cases for $\bar{r}$:

$$\lim_{\substack{b_2\to\infty \\ or\ a_2\to 0}} \bar{r}_{min} = 0\,, \tag{17}$$

$$\lim_{\substack{b_1,b_2\to 0 \\ or\ a_2\to\infty}} \bar{r} = 1 \tag{18}$$

From (13) and (15`), the allowable level of emissions under the intensity cap is:

$$e(\bar{r},\alpha) = \alpha\left(\bar{e} + \left(\frac{\sigma^2}{1+\sigma^2}\right)\left(\frac{b_1}{a_2+b_2}\right)\right) \tag{19}$$

We can also determine the resulting emissions price, using (4) and (19):

$$p(\bar{r},\alpha) = a_2\alpha - a_2\alpha\left(\bar{e} + \left(\frac{\sigma^2}{1+\sigma^2}\right)\left(\frac{b_1}{a_2+b_2}\right)\right) \tag{20}$$

Notice that the regulator's objective functions for the intensity cap (14) and the absolute cap (10) effectively differ by the last term in (14), which has σ^2 as its coefficient. Thus, unlike with the absolute cap, the regulator incorporates the degree of uncertainty with respect to BaU emissions when setting the intensity cap. The specific consequences of this will be discussed in Section 4.4. For now, we simply draw the reader's attention to two basic results. The first is that $\frac{\partial \bar{r}}{\partial \sigma^2} > 0$,[46] such that greater uncertainty on BaU emissions will be associated with a more lax intensity rate. Second, since $\left(\frac{\sigma^2}{1+\sigma^2}\right)\left(\frac{b_1}{a_2+b_2}\right) > 0$,

[45] Note that $\bar{r}_{min}$, the lower bound of $\bar{r}$, is defined where $b_1 = a_2$.

[46] $\frac{\partial \bar{r}}{\partial \sigma^2} = \frac{b_1}{(1+\sigma^2)^2(a_2+b_2)}$

(19) implies that $e(\bar{r},1) > \bar{e}$. In other words, allowable emissions levels will be greater on average under the intensity cap than under the absolute cap.

4.2.3 Price Instrument (P)

Under a price instrument, the regulator fixes the emission price p (which would likely be an emissions tax), and firms choose the level of emissions so as to equate their MAC and p. The resulting level of emissions, from (4) and $p = MAC$, is

$$e(p,\alpha) = \alpha - \frac{p}{a_2} \tag{21}$$

Substituting (21) into our expression for TSC (9) and taking the expectation leads to the regulator's social cost minimization problem for the price instrument:

$$\min_p E[TSC(P)] = E\left[\frac{a_2}{2}\alpha^2 + (b_1 - a_2\alpha)e(p,\alpha) + \left(\frac{a_2 + b_2}{2}\right)e(p,\alpha)^2\right]$$

which can be manipulated to yield

$$\min_p E[TSC(P)] = \frac{a_2}{2}(1+\sigma^2) + (b_2 - b_1)p + \left(\frac{a_2 + b_2}{2{a_2}^2}\right)p^2 + \left(\frac{b_2 - a_2}{2}\right)(1+\sigma^2) + b_1 \tag{22}$$

Taking the first order condition, we obtain the optimal level of the price instrument

$$\bar{p} = \frac{a_2(b_1 + b_2)}{a_2 + b_2} \tag{23}$$

Substituting (23) back into (21) gives us the level of emissions induced by the price instrument

$$e(\bar{p},\alpha) = \alpha - \frac{b_1 + b_2}{a_2 + b_2} \tag{24}$$

which can be expressed in terms of the absolute cap

$$e(\bar{p},\alpha) = \bar{e} + (\alpha - 1) \tag{24`}$$

Thus, we have that in expectation (when $\alpha = 1$), the price instrument will yield the same level of emissions as the absolute cap and deviations in BaU emissions are met 1 for 1 by changes in emission levels.

4.3 Instrument Choice

Before formally evaluating the relative performance of the intensity cap to the absolute cap and the price instrument under uncertainty with regards to BaU emissions (and thus abatement costs) [47], it should be noted that all three instruments are equivalent in the absence of such uncertainty. From (11), (19) and (24`), we have that if $\alpha = 1$ and $\sigma^2 = 0$, then $e(\bar{r}, 1) = e(\bar{p}, 1) = \bar{e}$. All three instruments yield the same level of emissions, and thus the same emissions price and TSC.

4.3.1 Evaluation of Instruments Relative to the Ex Post Optimum

A useful way of evaluating the performance of an instrument is to compare outcomes under the instrument to the ex post optimum. The ex post optimal level of emissions (e*) is that which equates ex post MAC (4) and MED (8) (minimizing TSC (9)). From (4) and (8), we have:

$$e^*(\alpha) = \frac{\alpha a_2 - b_1}{a_2 + b_2} \tag{25}$$

and the associated ex post optimal emissions price level (from (8) and (25))

$$p^*(\alpha) = \frac{a_2(b_1 + \alpha b_2)}{a_2 + b_2} \tag{26}$$

Figures 4 and 5 portray (in price-emissions space) the outcomes of the three instruments in two scenarios: when BaU emissions are lower than expected (Figure 4) and when BaU emissions are higher than expected (Figure 5). Thus, the ex post MAC curve is everywhere below the expected MAC in the former case, and everywhere above the expected MAC curve in the latter case. The lines labelled Q, P, and I are the schedules of price-emissions outcomes under the three instruments (the absolute cap, price instrument and intensity cap, respectively) for various realizations of BaU emissions. The intersection between the ex post MAC curve and a given instrument's price-emissions schedule denotes the price level

[47] Though our analysis is not explicitly concerned with the choice between the absolute emissions cap and the price instrument, it should be noted that Weitzman's criterion for choosing between the two is still valid with our formulation of abatement costs and emissions damages. The price instrument should be preferred to the absolute cap if and only if the slope of the MAC curve exceeds the slope of the MED curve.

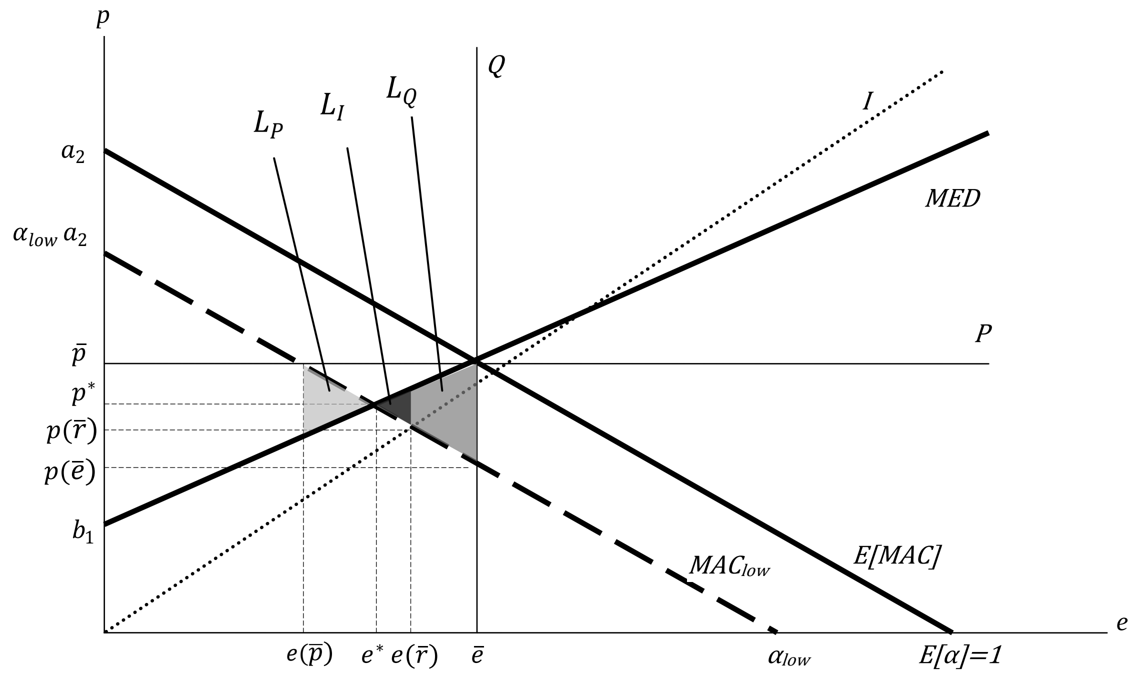

Figure 4. Outcomes of the three instruments with lower than expected BaU emissions ($\alpha < E[\alpha] = 1$).

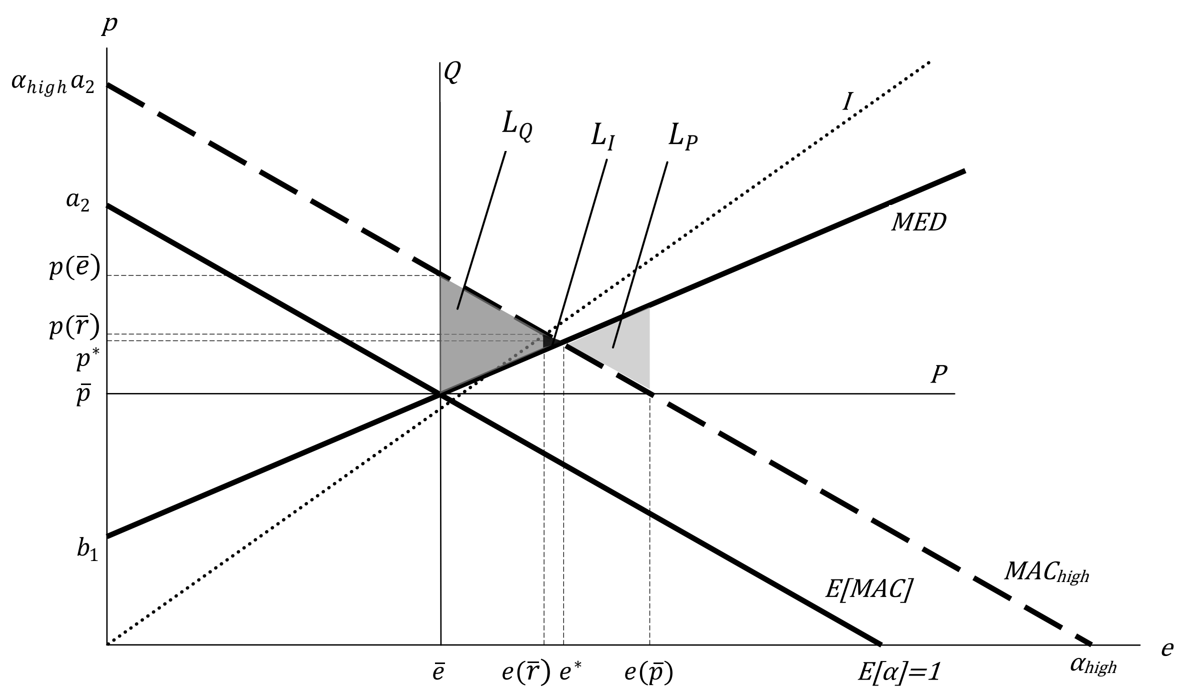

Figure 5. Outcomes of the three instruments with higher than expected BaU emissions ($\alpha > E[\alpha] = 1$).

and emissions level induced by that instrument. As with Figures 2 and 3, L_i represents the social loss under instrument i, which is the difference between total social cost under the instrument and total social cost at the ex post optimal level of emissions. Thus, $L_i = TSC(i) - TSC(e^*)$.

The first thing to note is that, in the examples shown, none of the instruments is able to induce the ex post optimum. In the low BaU emissions case, both the intensity cap and absolute cap yield emissions levels that are too high, while the price instrument yields an emissions level that is too low. In the high BaU emissions case, the reverse is true: the price instrument yields too high an emissions level while the intensity cap and absolute cap both yield emissions levels that are too low. In short, when α deviates from its expected value, emissions under the price instrument change too much while emissions under the intensity cap and absolute cap do not change enough (or at all, in the latter case). However, it is worth pointing out that in both of our examples, social losses under the intensity cap are smaller than social losses under the other two instruments.

Figure 6 again portrays the outcomes of the three instruments under two representative scenarios: lower than expected BaU emissions and higher than expected BaU emissions. Though social losses are not shown, we can see that the outcome under the intensity cap is in both cases closer to the ex post optimal outcome, when compared to the absolute cap. However, unlike with our previous examples (Figures 4 and 5), the outcome under the intensity cap is not obviously closer to the ex post optimum than the outcome under the price instrument in all cases. As shown, it is ambiguous which of the two instruments would be preferred in the case of lower than expected BaU emissions.

Abstracting from specific realizations of α, we can say something more general about the performance of the three instruments. Recalling that the ex post optimum is defined as the intersection between the MAC curve and the MED curve, one could imagine an optimal instrument which has a price-emissions schedule that exactly equals the MED curve, which represents the true social cost of emissions. Thus, we can judge an instrument based on how well or how poorly its price-emissions schedule approximates the MED curve. When the MED curve is relatively flat (i.e. b_2 is fairly low), it is better approximated by the price instrument than the intensity cap, which in turn provides a stronger approximation than the absolute cap. However, lower values of b_1 make for an MED curve that is closer in form to the price-emissions schedule of the intensity cap, at the expense of both other instruments.

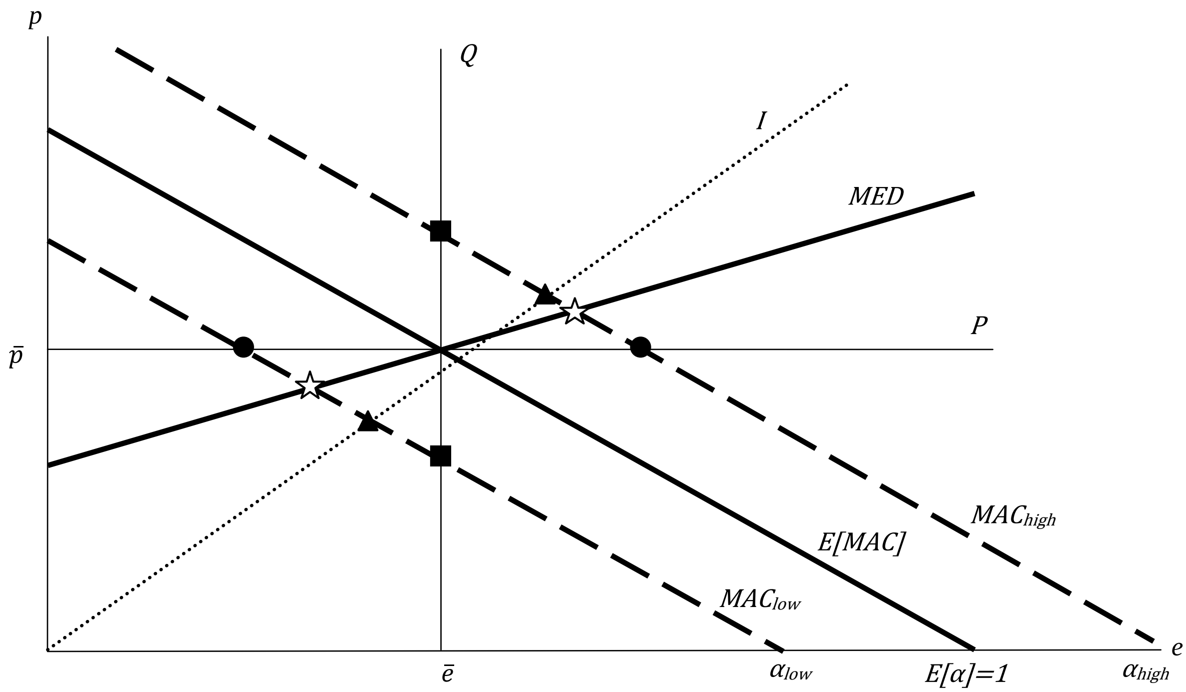

Figure 6. Outcomes of the three instruments under representative scenarios: lower than expected BaU emissions and higher than expected BaU emissions.

☆ - ex post optimal outcomes $\left(e^*(\alpha),\ p^*(\alpha)\right)$
■ - outcomes under the absolute cap $\left(\bar{e}, p(\bar{e}, \alpha)\right)$
● - outcomes under the price instrument $(e(\bar{p}, \alpha),\ \bar{p})$
▲ - outcomes under the intensity cap $\left(e(\bar{r}, \alpha), p(\bar{r}, \alpha)\right)$

Most importantly, we observe that the intensity cap has a fundamental 'advantage' over the other two instruments: its price-emissions schedule, like the MED curve, is positively sloped.[48] Moreover, the optimal intensity rate ($\bar{r}$) reflects the slope and intercept of the MED curve, such that the intensity cap's

[48] Thus, the intensity cap allows both the price level and the emissions level to vary in response to shifts in the MAC curve, while the other two instruments necessarily hold one of the two constant.

price-emissions schedule is effectively tailored to approximate the MED curve. The optimal price instrument and absolute cap, however, are set only based on the expected optimal outcome (i.e. where the MED curve and E[MAC] curves intersect, irrespective of the slopes and intercepts of these curves). The flexibility of the intensity cap is its main strength, and is the reason why its price-emissions schedule is always able to provide a better approximation of the MED curve than the price-emissions schedule of the absolute cap. This is consistent with the fundamental result of our model: that the intensity cap always dominates (i.e. results in lower social losses) the absolute cap. We now turn to the task of proving this result and exploring the instrument choice problem more formally.

4.3.2 Formal Instrument Choice Criterion

Intensity Cap vs. Absolute Cap

Our basic metric for comparing instruments is based on expected TSC. We thus define $\Delta_{Q,I}$ as the difference between the expected TSC of using the absolute cap and the expected TSC of using the intensity cap - the 'cost savings' of the intensity cap:

$$\Delta_{Q,I} = E[TSC(Q)] - E[TSC(I)] \tag{27}$$

which, using TSC (9) and (13) and taking the expectation, yields

$$\Delta_{Q,I} = (b_1 - a_2)(\bar{e} - \bar{r}) + \left(\frac{a_2 + b_2}{2}\right)(\bar{e}^2 - \bar{r}^2) - \sigma^2\left(-a_2\bar{r} + \left(\frac{a_2 + b_2}{2}\right)\bar{r}^2\right) \tag{28}$$

Substituting (11) and (15) into (28) and simplifying, we obtain the following:[49]

$$\Delta_{Q,I} = \sigma^2\left(\frac{{a_2}^2(1 + \sigma^2) - {b_1}^2}{2(1 + \sigma^2)(a_2 + b_2)}\right) \tag{26`}$$

Since $\Delta_{Q,I}$ represents the cost savings associated with use of the intensity cap rather than the absolute cap, the intensity cap will be preferred to the absolute cap whenever $\Delta_{Q,I} > 0$, the absolute cap will be preferred whenever $\Delta_{Q,I} < 0$, and the regulator will be indifferent between the two instruments whenever

[49] Detailed calculations can be found in Appendix A.

$\Delta_{Q,I}= 0$. Since $\sigma^2 > 0$ and $a_2 \geq b_1$[50], it must be that $a_2\sqrt{(1+\sigma^2)} > b_1$[51]. This implies that $\Delta_{Q,I}> 0$ will always hold. Thus, we find that the intensity cap will *always* be preferred to the absolute cap, which is the fundamental result of this model.

Since $\Delta_{Q,I}$ will always be positive under our assumptions, it can be shown that $\frac{\partial\Delta_{Q,I}}{\partial\sigma^2}, \frac{\partial\Delta_{Q,I}}{\partial a_2} > 0$ and $\frac{\partial\Delta_{Q,I}}{\partial b_2}, \frac{\partial\Delta_{Q,I}}{\partial b_1} < 0$. This suggests that a higher variance of BaU emissions and a steeper MAC curve serve to increase the cost savings associated with the intensity cap (as compared to the absolute cap). On the other hand, a steeper MED curve and a larger MED intercept both serve to reduce the cost savings associated with the intensity cap. These results are consistent with our observations from Section 4.3.1: increasing the slope of the MED curve moves it closer in form to the price-emissions schedule of the absolute cap (i.e. a vertical line), thus diminishing the intensity cap's relative advantage. Similarly, because the intensity cap's price-emissions schedule must go through the origin, it does a poorer job of approximating the MED curve when the MED curve's intercept is larger.

Intensity Cap vs. Price Instrument

Let $\Delta_{P,I}$ be the difference between the expected TSC of using the price instrument and the expected TSC of using the intensity cap:

$$\Delta_{P,I}= E[TSC(P)] - E[TSC(I)] \tag{29}$$

which, using TSC(9) can be expanded to yield

$$\Delta_{P,I}= E\left[(b_1 - a_2\alpha)(e(\bar{p},\alpha) - e(\bar{r},\alpha)) + \left(\frac{a_2+b_2}{2}\right)((e(\bar{p},\alpha)^2 - e(\bar{r},\alpha)^2)\right] \tag{30}$$

Substituting (13) and (24`) into (30) and simplifying, it can be shown that:

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[50] Recall that $a_2 > b_1$must hold in order to ensure that the optimal level of emissions is non-negative (a basic assumption).

[51] From ${a_2}^2(1+\sigma^2) - {b_1}^2 > 0$.

$$\Delta_{P,I} = \Delta_{Q,I} + \sigma^2 \left(\frac{b_2 - a_2}{2}\right) \tag{31}$$

Thus, by (26`) and (31), we obtain the following:

$$\Delta_{P,I} = \sigma^2 \left(\frac{{b_2}^2(1+\sigma^2) - {b_1}^2}{2(1+\sigma^2)(a_2+b_2)}\right) \tag{32}$$

The intensity cap will be preferred to the price instrument whenever $\Delta_{P,I} > 0$, the price instrument will be preferred whenever $\Delta_{P,I} < 0$, and the regulator will be indifferent between the two instruments whenever $\Delta_{P,I} = 0$. From (32), greater variance of BaU emissions tends to favour the use of the intensity target, though it should be noted that the sign of $\frac{\partial \Delta_{P,I}}{\partial \sigma^2}$ itself is ambiguous. A steeper MED curve tends to favour the use of the intensity cap, a larger MED intercept tends to favour the use of the price instrument, *and* it can be shown that $\frac{\partial \Delta_{P,I}}{\partial b_2} > 0$ and $\frac{\partial \Delta_{P,I}}{\partial b_1} < 0$. Again, these results are consistent with our observations from Section 4.3.1. A flat MED curve with a relatively large intercept is fairly well approximated by the price-emissions schedule of the price instrument (i.e. a flat line) while a steep MED curve with an intercept closer to the origin is better approximated by the positively slope price-emissions schedule of the intensity cap. Finally, regardless of which instrument dominates, increasing the slope of the MAC curve will reduce that instrument's relative advantage over the other.

4.3.3 Ranking of Instruments

Having derived the conditions for choosing between the intensity cap and the other two instruments, we now turn to the task of examining in more detail the relationship between the ranking of the instruments and the parameters. We begin by presenting the following key identities:

$$\Delta_{Q,I} \equiv \Delta_{Q,P} + \Delta_{P,I} \tag{33}$$

$$\Delta_{P,I} \equiv \Delta_{Q,I} - \Delta_{Q,P} \tag{34}$$

where $\Delta_{Q,I} > 0$ (recall that the intensity cap always dominates the absolute cap) and $\Delta_{Q,P}$ is defined as the cost savings associated with use of the price instrument relative to the absolute cap. It can be shown that[52]:

$$\Delta_{Q,P} = \sigma^2 \left(\frac{a_2 - b_2}{2}\right) \tag{35}$$

Using (35), (26`) and (32)[53], we can derive the following conditions for choosing between each pair of instruments:

$$I \succ Q \iff \Delta_{Q,I} > 0 \quad \forall \quad 0 \le b_1 \le a_2, b_2 \ge 0 \text{ }^{54} \tag{36}$$

$$P \succ Q \iff \Delta_{Q,P} > 0 \quad \forall \quad a_2 > b_2 \tag{37}$$

$$Q \succ P \iff \Delta_{Q,P} < 0 \quad \forall \quad a_2 < b_2 \tag{38}$$

$$I \succ P \iff \Delta_{P,I} > 0 \quad \forall \quad b_2\sqrt{(1+\sigma^2)} > b_1 \tag{39}$$

$$P \succ I \iff \Delta_{P,I} < 0 \quad \forall \quad b_2\sqrt{(1+\sigma^2)} < b_1 \tag{40}$$

Using these expressions, we can define indifference lines that represent the parameter values for which the regulator will be indifferent between two of the instruments. The *Q/P* indifference line is defined as follows:

$$Q \approx P \iff \Delta_{Q,P} = 0 \quad \forall \quad a_2 = b_2 \tag{41}$$

Similarly, the *P/I* indifference line is defined as:

$$I \approx P \iff \Delta_{P,I} = 0 \quad \forall \quad b_2\sqrt{(1+\sigma^2)} = b_1 \tag{42}$$

---

[52] Note that, as expected, Weitzman's criteria for choosing between the absolute cap and the price instrument applies in this case. The price instrument will be preferred ($\Delta_{Q,I} > 0$) if the slope of the MAC curve exceeds that of the marginal damage curve ($a_2 > b_2$), the absolute cap will be preferred ($\Delta_{Q,I} < 0$) if the slope of the MAC curve is less than that of the marginal damage curve ($a_2 < b_2$), and the regulator will be indifferent between the two instruments ($\Delta_{Q,I} = 0$) when the slopes of the two curves are the same ($a_2 = b_2$).

[53] See Section 4.3.2.

[54] Note that these conditions represent our basic assumptions about the paramaters, such that the intensity cap always dominates the absolute cap under our assumptions.

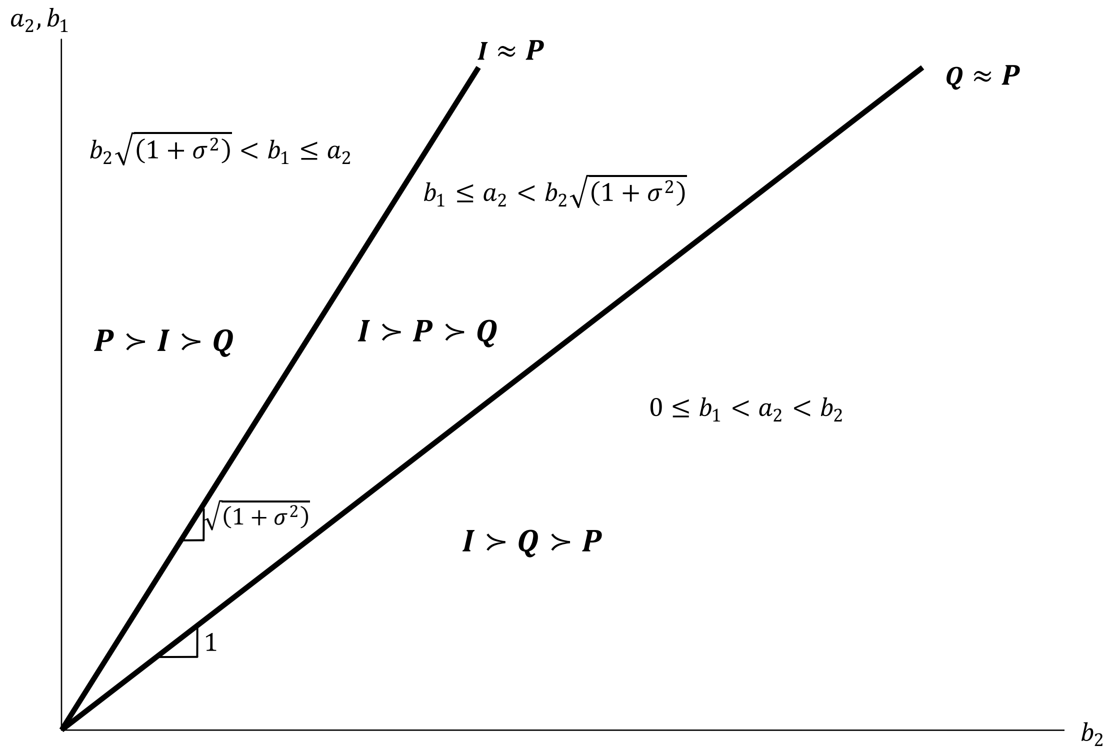

Figure 7. Ranking of the three instruments in the parameter space.

Figure 7 displays the ranking of the three instruments in the (a_2, b_1; b_2) parameter space. The intensity cap is the preferred instrument for any parameter combination below the *P/I* indifference line, while the price instrument is the preferred instrument for any parameter combination above it. The *Q/P* indifference line marks the split between the parameter spaces where the price instrument dominates the absolute cap (above the line) and vice-versa (below the line). Notice that the *Q/P* indifference line is unaffected by the degree of uncertainty in BaU emissions (σ^2). The *P/I* indifference line, on the other hand, becomes steeper as σ^2 increases. Thus, with greater uncertainty, the parameter range for which $P \succ I \succ Q$ becomes smaller. This means that when uncertainty is high, the intensity cap will generally (i.e. over most of the parameter space) be the dominant instrument. As $\sigma^2 \to 0$ however, the *P/I* indifference line converges on the *Q/P* indifference line and we approach the case where the three instruments are equivalent ($I \approx Q \approx P$).

4.4 Instrument Performance

4.4.1 Emissions Schedules, Price Schedules, and Instrument Convergence Properties

Table 1. Key information on the performance of the three instruments.

	Price instrument, $\bar{\boldsymbol{p}}$	Absolute cap, $\bar{\boldsymbol{e}}$	Intensity cap, $\bar{\boldsymbol{r}}$
Optimal instrument; price and emission schedules	$\bar{p} = \frac{a_2(b_1 + b_2)}{a_2 + b_2}$ $e(\bar{p}, \alpha) = \alpha - \frac{\bar{p}}{a_2}$	$\bar{e} = \frac{a_2 - b_1}{a_2 + b_2}$ $p(\bar{e}, \alpha) = a_2(\alpha - \bar{e})$	$\bar{r} = \bar{e} + \left(\frac{\sigma^2}{1 + \sigma^2}\right)\left(\frac{b_1}{a_2 + b_2}\right)$ $p(\bar{r}, \alpha) = \alpha a_2(1 - \bar{r})$ $e(\bar{r}, \alpha) = \alpha(\bar{r})$
Expected price and emissions level	$Price\ is\ fixed\ at\ \bar{p}$ $E[e(\bar{p}, \alpha)] = \bar{e}$	$E[p(\bar{e}, \alpha)] = a_2(1 - \bar{e})$ $Emissions\ are\ fixed\ at\ \bar{e}$	$E[p(\bar{r}, \alpha)] = a_2(1 - \bar{r})$ $E[e(\bar{r}, \alpha)] = \bar{r}$
Variance of price and emissions level	$var(\bar{p}) = 0$ $var\big(e(\bar{p}, \alpha)\big) = \sigma^2$	$var\big(p(\bar{e}, \alpha)\big) = \sigma^2 {a_2}^2$ $var(\bar{e}) = 0$	$var\big(p(\bar{r}, \alpha)\big) = \sigma^2 {a_2}^2 (1 - \bar{r})^2 = (1 - \bar{r})^2 var\big(p(\bar{e}, \alpha)\big)$ $var\big(e(\bar{r}, \alpha)\big) = \sigma^2 \bar{r}^2 = \bar{r}^2 var\big(e(\bar{p}, \alpha)\big)$

In order to better understand the relationship between the intensity cap and the other instruments, it is useful to examine the emissions and price schedules, as well the variances of emissions and price under each instrument.

An important depiction of the performance of the three instruments relative to the ex post optimum involves graphing the associated emissions and price schedules (as a function of ex post BaU emissions, α). In comparing the performance of the instruments relative to the ex post optimum, we are building upon our discussion of instrument ranking from Section 4.3.1. To do this, we first specify a distribution for α which ensures that the optimal emissions level is always positive. Assuming α follows a continuous uniform distribution, then ensuring a positive optimal emissions level implies that the distribution of α must have a lower bound of at least $\frac{b_1}{a_2}$[55], and an associated upper bound that is no greater than $2 - \frac{b_1}{a_2}$. Thus, we have that

$$\frac{b_1}{a_2} \leq \alpha_{min} < E[\alpha] = 1 < \alpha_{max} \leq 2 - \frac{b_1}{a_2}$$

This constraint implies a maximum variance of α:

$$\sigma^2 \leq \frac{(1 - \frac{b_1}{a_2})^2}{3} \tag{43}$$

Figures 8 and 9 display the emissions and price schedules[56] (respectively) of all three instruments as well as the ex post optimal schedules over a range of possible values for α. In the example shown, σ^2 is set at its maximum value such that optimal emissions would be zero when α equals its lower bound.[57]

In terms of the slopes of the emissions and price schedules, both the intensity cap and the ex post optimum lie somewhere between the extremes of the absolute cap and the price instrument. Further, the intensity cap is closer in slope to the ex post optimum than is the absolute cap, while it is ambiguous as to whether the intensity cap or the price instrument comes closer to the ex post optimum. This is consistent with two of our basic results - that the regulator should always prefer the intensity cap to the absolute cap, whereas the choice between the intensity cap and the price instrument will depend upon the slope and intercept of the MED curve and the degree of uncertainty about BaU emissions (σ^2). A less formal interpretation reflects our earlier observation: the intensity cap is generally more successful than the absolute cap at inducing emissions and price schedules that approximate the ex post optimal schedules.[58]

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[55] From $e^*(\alpha) = \frac{\alpha a_2 - b_1}{a_2 + b_2} = 0 \Rightarrow \alpha = \frac{b_1}{a_2}$

[56] See Table 1.

[57] Note that although Figures 8 and 9 depict a specific example, the basic features of the emissions and price schedules (such as the ranking of the slopes of the schedules) apply in general.

[58] Note that even though the intensity cap is always preferred to the absolute cap ex ante, this does *not* imply that ex post TSC will be lower with the intensity cap for every possible realization of α. In fact, there is a small

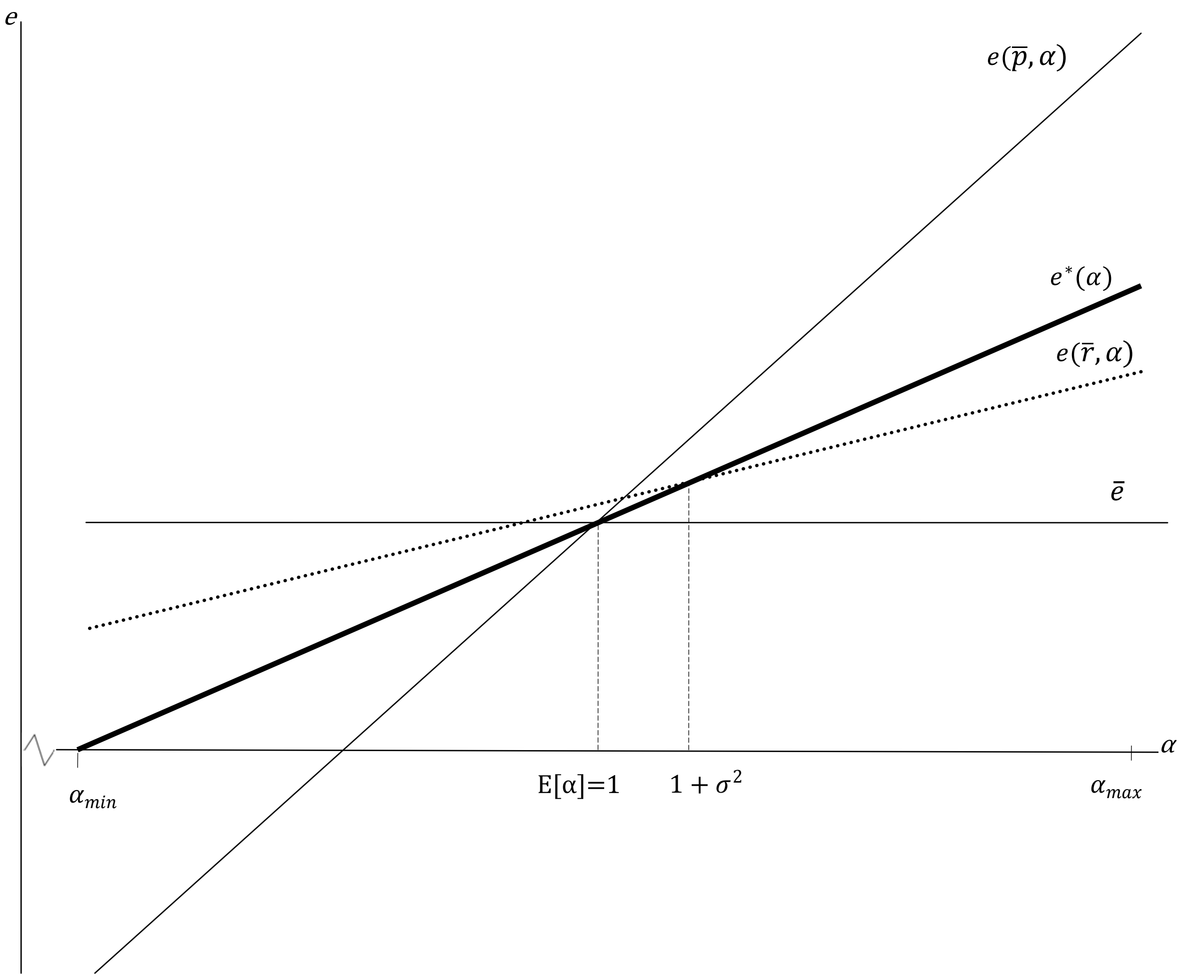


Figure 8. Emissions schedules for all three instruments and the ex post optimum. To scale for parameter values: $\boldsymbol{b_1 = 0.5}$ and $\boldsymbol{a_2 = b_2 = 1}$, such that $\boldsymbol{\alpha_{min} = 0.5}$, $\boldsymbol{\alpha_{min} = 1.5}$ and $\boldsymbol{\sigma^2} \cong \boldsymbol{0.08}$, $\boldsymbol{\sigma} \cong \boldsymbol{0.29}$.

(asymmetric) range of values of α around *E[α]* for which the absolute cap will yield an emissions level closer to the ex post optimal level. This range can be shown to be: $1 - \frac{b_1\sigma^2}{a_2(1+\sigma^2)-b_1} < \alpha < 1 + \frac{b_1\sigma^2}{a_2(1+\sigma^2)+b_1}$.

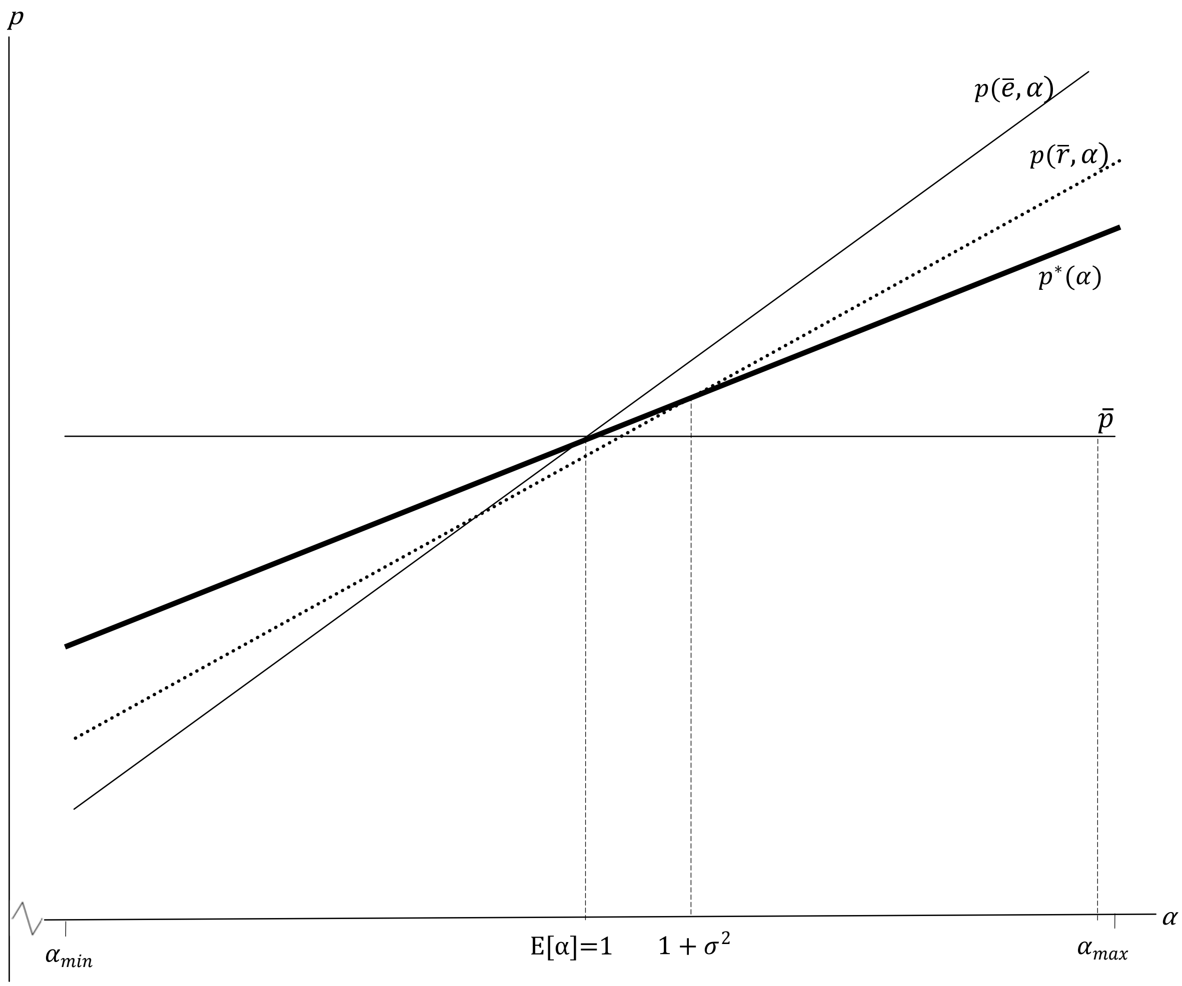


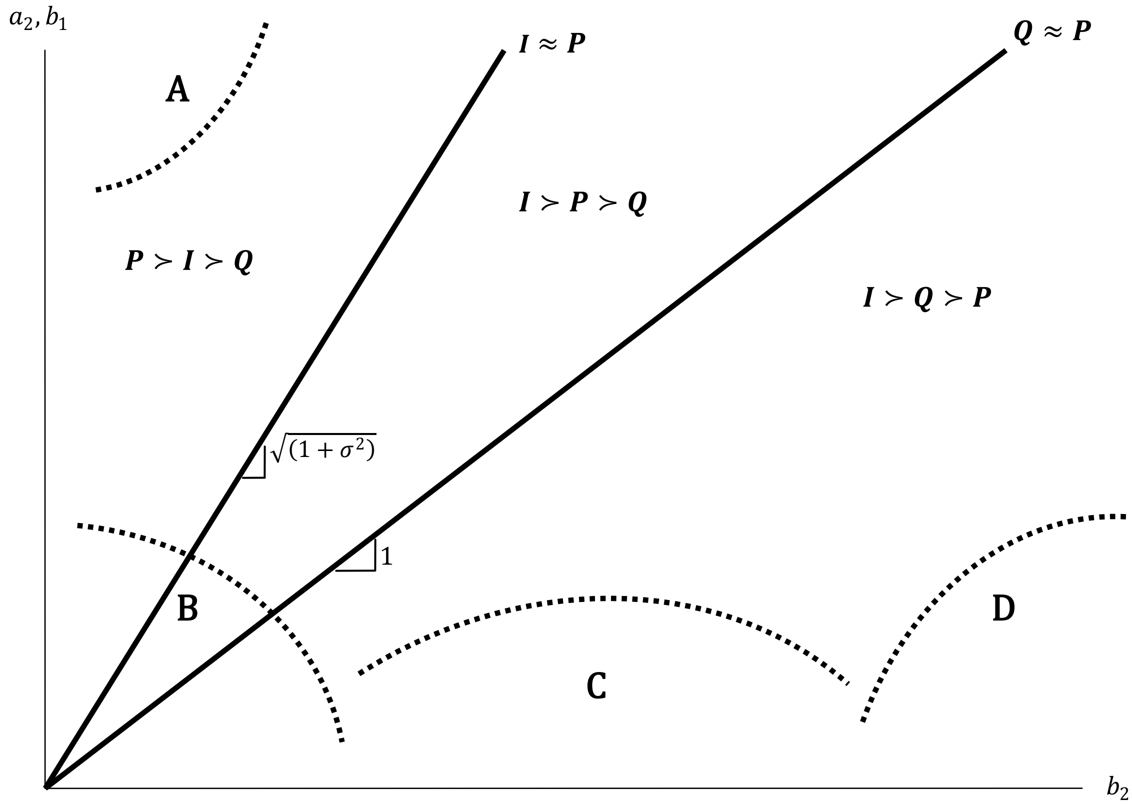
Figure 9. Price schedules for all three instruments and the ex post optimum. To scale for parameter values: $\boldsymbol{b_1 = 0.5}$ and $\boldsymbol{a_2 = b_2 = 1}$; $\boldsymbol{\alpha_{min} = 0.5}$, $\boldsymbol{\alpha_{min} = 1.5}$ and $\boldsymbol{\sigma^2 \cong 0.08}$, $\boldsymbol{\sigma \cong 0.29}$.

Examining the emissions and price schedules also provides further insights into how the intensity cap explicitly accounts for uncertainty on α. Recall that $\frac{\partial \bar{r}}{\partial \sigma^2} > 0$ - the intensity rate becomes more lax as uncertainty on α increases. As a consequence, greater uncertainty increases the slope of the intensity cap's emissions schedule and decreases the slope of the price schedule. Thus, there appears to be an implicit aversion to variations in the MAC – when faced with greater uncertainty on BaU emissions, the regulator's optimal response is to increase the intensity rate, thereby decreasing the variation in the abatement level and MAC associated with any given deviation of BaU emissions from its expected value. With the absolute cap however, adjusting the policy will have no affect on the variations in ex post MAC stemming from variations in α.

The emissions and price schedules shown in Figures 8 and 9 provide us with depictions of how the intensity cap differs from that of the other two instruments. However, precisely because it is a flexible instrument that is very closely tied to the slopes and positions of the MED and MAC curves, the optimal intensity cap will in certain instances behave similarly to either the price instrument or the absolute cap. Using our expressions for the limiting cases of $\bar{r}$ ((17) and (18)) in combination with our expressions for the variances of the price and emissions levels from Table 1 enables us to describe the cases where the intensity cap behaves most closely like the other instruments. As $\bar{r} \to 0$, $var\big(p(\bar{r},\alpha)\big) \to var\big(p(\bar{e},\alpha)\big)$ and $var\big(e(\bar{r},\alpha)\big) \to 0$, such that $I \to Q$. Thus, when the MED curve is steep (i.e. high values of b_2) and/or the MAC curve is flat (i.e. low values of a_2), the intensity cap behaves similarly to the absolute cap, with emissions held constant and relatively large variations in price. Conversely, as $\bar{r} \to 1$, $var\big(p(\bar{r},\alpha)\big) \to 0$ and $var\big(e(\bar{r},\alpha)\big) \to var\big(e(\bar{p},\alpha)\big)$, such that $I \to P$. When the MED curve is low and flat (i.e. low values of b_1 and b_2) and/or the MAC curve is steep (i.e. high values of a_2), the intensity cap behaves much like the price instrument, with relatively large variations in emissions and price held constant.

4.4.2 Summary and Applications

Drawing upon our analysis and key insights in Sections 4.3 and 4.4.1, we can identify key regions in the parameter space where particular instruments will have their largest (and smallest) advantages over the other two. These regions are displayed in Figure 10. Again, it is crucial to note that the intensity cap is almost always the dominant instrument. Moreover, the only circumstance where the price instrument's advantage over the intensity cap is significant is when the MED curve is quite flat, the intercept of the marginal damage curve is quite high, and the slope of the MAC curve is low. The intensity cap's



Region	**A**	**B**	**C**	**D**
General	Gains from use of *P* are the greatest Losses from use of *Q* are greatest	Gains/losses from use of *I* are smallest	Gains from use of *I* are greatest	Gains from use of *Q* are greatest Loses from use of *P* are greatest
I vs.P	$\Delta_{P,I}$ small, - $\Leftrightarrow P \gtrsim I$ $var(p(\bar{r},\alpha)) \to 0$, $var(e(\bar{r},\alpha)) \to var(e(\bar{p},\alpha))$, $and\ \bar{r} \to 1\ as\ a_2 \to \infty$ $\Rightarrow I \to P$	$\Delta_{P,I}$ small +/- $\Leftrightarrow I \cong P$ $var(p(\bar{r},\alpha)) \to 0$, $var(e(\bar{r},\alpha)) \to var(e(\bar{p},\alpha))$, $and\ \bar{r} \to 1\ as\ b_1, b_2 \to 0$ $\Rightarrow I \to P$	$\Delta_{P,I}$ + $\Leftrightarrow I \succ P$	$\Delta_{P,I}$ large, + $\Leftrightarrow I \succ\succ P$
I vs. Q	$\Delta_{Q,I}$ large, + $\Leftrightarrow I \succ\succ Q$	$\Delta_{Q,I}$ + $\Leftrightarrow I \succ Q$	$\Delta_{Q,I}$ + $\Leftrightarrow I \succ Q$	$\Delta_{Q,I}$ small, + $\Leftrightarrow I \gtrsim Q$ $var(p(\bar{r},\alpha)) \to var(p(\bar{e},\alpha))$, $var(e(\bar{r},\alpha))$ and $\bar{r} \to 0$ $as\ a_2 \to 0\ or\ b_2 \to \infty$ $\Rightarrow I \to P$
Q vs. P	$\Delta_{Q,P}$ large, + $\Leftrightarrow P \succ\succ Q$	Ambiguous	$\Delta_{Q,P}$ - $\Leftrightarrow Q \succ P$	$\Delta_{Q,P}$ large, - $\Leftrightarrow Q \succ\succ P$

Figure 10. Key regions in the parameter space.

advantage over the price instrument is the most significant in region D, where the slope of the MED curve is high, the intercept of the MED curve is low and the slope of the MAC curve is low. Conversely, when the slope of the MED curve is low, the intercept of the MED curve is high and the slope of the MAC curve is high (region A), the intensity cap's advantage over the absolute cap is at its greatest. Finally, we can identify region C as the region where, in a three-way comparison between the instruments, the intensity cap is most clearly dominant. The key feature of this region is a low MED intercept, which, recalling our discussion in Section 4.3.1, allows the price-emissions schedule of the intensity cap to better approximate the MED curve, relative to *both* other instruments.

One of the basic insights from our model is that intensity cap can be characterized as lying somewhere between a price instrument and an absolute cap. In addition, we have shown that the intensity cap is indeed the preferred instrument over a very wide range of possible parameter values. This is in sharp contrast to Quirion's model, which finds little 'room' for the intensity cap.

We may, however, wish to focus on the most plausible/common cases, which (as Quirion (2005) points out) are the extreme cases where the MED curve is either relatively flat or very steep (as with persistent organic pollutants or any pollutant where threshold effects are important). In the former case, the choice between the intensity cap and the price instrument is likely to be ambiguous according to our model. Note that Quirion's model, by contrast, leads him towards a stronger endorsement of price instruments in this case. However, on the specific issue of climate change, our findings support Quirion's. It has been argued that price instruments would be preferred to absolute caps in the context of climate policy (see, for example, Newell and Pizer 2003), primarily because estimates of the marginal damages from GHG emissions indicate that they are likely to be essentially flat relative to marginal abatement costs. Our model suggests that an intensity cap would also be preferred to an absolute cap. Moreover, propositions of a carbon tax have so far proven to be politically unpopular, making an intensity cap an attractive alternative.

In the case of a steep MED curve, our model leads us to conclude that an intensity cap would still be preferred to an absolute cap, which is a key departure from Quirion's endorsement of an absolute cap in such circumstances. We attribute this result to our different assumptions about the nature of abatement costs. Specifically, when marginal abatement cost is a function of relative abatement (as Quirion assumes), an intensity cap will behave much like a price instrument, which Weitzman's (1974) criterion shows is inferior to an absolute cap when damages are relatively steep. In a context where marginal abatement cost is a function of absolute abatement (as we assume), an intensity cap will operate more as a flexible quantity instrument that can always yield lower expected total social costs than an absolute cap.

5 Conclusions

In order to provide further insights into the performance under uncertainty of an emissions intensity cap relative to an absolute emissions cap and (to a lesser extent) a price instrument, this paper has presented a model which extends Quirion's (2005) model to the case where marginal abatement cost is a function of absolute abatement, as opposed to relative abatement. Specifically, we have examined expected total social costs under each of the three instruments. This has been complemented by an analysis of how our approach to modeling abatement costs impacts the specific way in which an intensity cap will perform in different contexts.

The fundamental result of our model is that, under uncertainty with regards to business-as-usual (BaU) emissions, an intensity cap will always be preferred to an absolute cap. Driving this result is the fact that the optimal intensity cap effectively takes into account the degree of uncertainty on BaU emissions and consistently does a better job of internalizing the marginal environmental damage (MED) curve. The cost savings from using an intensity cap will be greatest when the MED curve is relatively flat, the intercept of the MED curve is low, uncertainty on BaU emissions is high and the marginal abatement cost (MAC) curve is relatively steep. As such, we find that an intensity cap would likely be an effective policy instrument for addressing emissions of greenhouse gases.

Comparing an intensity cap to a price instrument, we find that the intensity cap is most likely to dominate when the MED curve is steep, the intercept of the MED curve is low, and uncertainty on BaU emissions is high.

Overall, we find that an intensity cap is the dominant instrument for a very wide range of parameter values. This finding is in sharp contrast to Quirion, whose model leads him to conclude that an intensity cap is almost always dominated by either an absolute cap or price instrument.[59] We attribute our results to the flexibility of the intensity cap in our model. In Quirion's model, the intensity cap behaves identically to the price instrument in response to changes in BaU emissions, in that both serve to fix the price of emissions. In our model, the intensity cap falls somewhere between the price instrument and the absolute cap: it allows both price and emissions to vary in response to changes in BaU emissions. In addition, relative to the other two instruments, we find that the optimal intensity cap is more closely tailored to the position and shape of the MED curve, as well as the degree of uncertainty about BaU emissions.

[59] On a methodological note, the choice of whether to model abatement costs as a function of relative or absolute abatement has an important impact on the performance of an intensity cap. As such, a policy maker faced with a choice between an intensity cap and absolute cap may want to factor into their decision whether abatement costs are likely to be determined by relative or absolute emissions abatement, with the former favouring the absolute cap and the latter favouring the intensity cap.

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Appendix A Derivation of $\Delta_{Q,I}$ and $\Delta_{P,I}$

A.1 $\Delta_{Q,I}$

In order to derive our final expression for $\Delta_{Q,I}$ we begin with equation (28):

$$\Delta_{Q,I} = (b_1 - a_2)(\bar{e} - \bar{r}) + \left(\frac{a_2 + b_2}{2}\right)(\bar{e}^2 - \bar{r}^2) - \sigma^2\left(-a_2\bar{r} + \left(\frac{a_2 + b_2}{2}\right)\bar{r}^2\right) \tag{28}$$

Recall the expressions for the optimal absolute cap ($\bar{e}$ (11)) and the optimal intensity cap ($\bar{r}$ (15)):

$$\bar{e} = \frac{a_2 - b_1}{a_2 + b_2} \tag{11}$$

$$\bar{r} = \frac{a_2(1 + \sigma^2) - b_1}{(a_2 + b_2)(1 + \sigma^2)} \tag{15}$$

Substituting the above expressions into (28) yields:

$$\begin{aligned}\Delta_{Q,I} = {} & (b_1 - a_2)\left(\frac{a_2 - b_1}{a_2 + b_2} - \frac{a_2(1 + \sigma^2) - b_1}{(a_2 + b_2)(1 + \sigma^2)}\right) \\ & + \left(\frac{a_2 + b_2}{2}\right)\left(\frac{(a_2 - b_1)^2}{(a_2 + b_2)^2} - \frac{(a_2(1 + \sigma^2) - b_1)^2}{(a_2 + b_2)^2(1 + \sigma^2)^2}\right) \\ & - \sigma^2\left(-a_2\left(\frac{a_2(1 + \sigma^2) - b_1}{(a_2 + b_2)(1 + \sigma^2)}\right) + \left(\frac{a_2 + b_2}{2}\right)\left(\frac{(a_2(1 + \sigma^2) - b_1)^2}{(a_2 + b_2)^2(1 + \sigma^2)^2}\right)\right)\end{aligned}$$

$$\begin{aligned}\Delta_{Q,I} = {} & (a_2(1 + \sigma^2) - b_1)\left(\frac{a_2(1 + \sigma^2) - b_1}{(a_2 + b_2)(1 + \sigma^2)}\right) - \left(\frac{a_2 + b_2}{2}\right)(1 + \sigma^2)\left(\frac{(a_2(1 + \sigma^2) - b_1)^2}{(a_2 + b_2)^2(1 + \sigma^2)^2}\right) \\ & - \frac{(a_2 - b_1)^2}{(a_2 + b_2)} + \left(\frac{a_2 + b_2}{2}\right)\left(\frac{(a_2 - b_1)^2}{(a_2 + b_2)^2}\right)\end{aligned}$$

$$\Delta_{Q,I} = \frac{2(a_2(1 + \sigma^2) - b_1)^2 - (a_2(1 + \sigma^2) - b_1)^2}{2(1 + \sigma^2)(a_2 + b_2)} + \frac{-2(a_2 - b_1)^2 + (a_2 - b_1)^2}{2(a_2 + b_2)}$$

$$\Delta_{Q,I} = \frac{(a_2(1 + \sigma^2) - b_1)^2 - (1 + \sigma^2)(a_2 - b_1)^2}{2(1 + \sigma^2)(a_2 + b_2)}$$

$$\Delta_{Q,I} = \frac{{a_2}^2(1+\sigma^2)^2 - 2a_2b_1(1+\sigma^2) + {b_1}^2 - {a_2}^2(1+\sigma^2) + 2a_2b_1(1+\sigma^2) - {b_1}^2(1+\sigma^2)}{2(1+\sigma^2)(a_2+b_2)}$$

$$\Delta_{Q,I} = \frac{{a_2}^2(1+\sigma^2)(1+\sigma^2-1) + {b_1}^2(1-(1+\sigma^2))}{2(1+\sigma^2)(a_2+b_2)}$$

$$\Delta_{Q,I} = \frac{\sigma^2({a_2}^2(1+\sigma^2) - {b_1}^2)}{2(1+\sigma^2)(a_2+b_2)}$$

$$\Delta_{Q,I} = \sigma^2\left(\frac{{a_2}^2(1+\sigma^2) - {b_1}^2}{2(1+\sigma^2)(a_2+b_2)}\right) \qquad (26`)$$

A.2 $\Delta_{P,I}$

In order to derive our final expression for $\Delta_{P,I}$ we begin with equation (30):

$$\Delta_{P,I} = E\left[(b_1 - a_2\alpha)(e(\bar{p},\alpha) - e(\bar{r},\alpha)) + \left(\frac{a_2+b_2}{2}\right)((e(\bar{p},\alpha)^2 - e(\bar{r},\alpha)^2)\right] \qquad (30)$$

Recall the basic expression for emissions under an intensity cap (13) and the expression for emissions under the optimal price instrument ($e(\bar{p},\alpha)$ (24`)):

$$e(\bar{r},\alpha) = \bar{r}\alpha \qquad (13)$$

$$e(\bar{p},\alpha) = \bar{e} + (\alpha - 1) \qquad (24`)$$

Substituting these expressions into (30) yields:

$$\Delta_{P,I} = E\left[(b_1 - a_2\alpha)(\bar{e} + (\alpha-1) - \bar{r}\alpha) + \left(\frac{a_2+b_2}{2}\right)((\bar{e} + (\alpha-1))^2 - \bar{r}^2\alpha^2)\right]$$

$$\Delta_{P,I} = E\Big[(b_1 - a_2\alpha)\bar{e} + b_1(\alpha-1) - a_2\alpha^2 + a_2 + b_1\bar{r}\alpha - a_2\bar{r}\alpha^2$$
$$+ \left(\frac{a_2+b_2}{2}\right)(\bar{e}^2 + 2\bar{e}(\alpha-1) + \alpha^2 - 2\alpha + 1 - \bar{r}^2\alpha^2)\Big]$$

$$\Delta_{P,I} = (b_1 - a_2)\bar{e} - a_2(1+\sigma^2) + a_2 + b_1\bar{r} - a_2\bar{r}(1+\sigma^2)$$
$$+ \left(\frac{a_2+b_2}{2}\right)(\bar{e}^2 + (1+\sigma^2) - 1 - \bar{r}^2(1+\sigma^2))$$

$$\Delta_{P,I} = (b_1 - a_2)(\bar{e} - \bar{r}) + \left(\frac{a_2 + b_2}{2}\right)(\bar{e}^2 - \bar{r}^2) - \sigma^2 \left(-a_2\bar{r} + \left(\frac{a_2 + b_2}{2}\right)\bar{r}^2\right) + \sigma^2 \left(-a_2 + \left(\frac{a_2 + b_2}{2}\right)\right)$$

Notice that (from (28)) the first three terms form $\Delta_{Q,I}$. Thus we have

$$\Delta_{P,I} = \Delta_{Q,I} + \sigma^2 \left(\frac{b_2 - a_2}{2}\right) \tag{44}$$

Substituting (26`) into (45) gives us

$$\Delta_{P,I} = \sigma^2 \left(\frac{{a_2}^2(1 + \sigma^2) - {b_1}^2}{2(1 + \sigma^2)(a_2 + b_2)}\right) + \sigma^2 \left(\frac{b_2 - a_2}{2}\right)$$

$$\Delta_{P,I} = \sigma^2 \left(\frac{{a_2}^2(1 + \sigma^2) - {b_1}^2 + (b_2 - a_2)(a_2 + b_2)(1 + \sigma^2)}{2(1 + \sigma^2)(a_2 + b_2)}\right)$$

$$\Delta_{P,I} = \sigma^2 \left(\frac{{a_2}^2(1 + \sigma^2) - {b_1}^2 + ({b_2}^2 - {a_2}^2)(1 + \sigma^2)}{2(1 + \sigma^2)(a_2 + b_2)}\right)$$

$$\Delta_{P,I} = \sigma^2 \left(\frac{{a_2}^2(1 + \sigma^2) - {b_1}^2 + {b_2}^2(1 + \sigma^2) - {a_2}^2(1 + \sigma^2))}{2(1 + \sigma^2)(a_2 + b_2)}\right)$$

$$\Delta_{P,I} = \sigma^2 \left(\frac{{b_2}^2(1 + \sigma^2) - {b_1}^2}{2(1 + \sigma^2)(a_2 + b_2)}\right) \tag{32}$$