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On the comparative advantage of tradable emission permits in a setting of uncertain abatement costs and market power
– A case against the invariably pessimistic view

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Abstract. Recent work has shown that Weitzman's policy rule for choosing price- versus quantity-based pollution control instruments under uncertainty is biased when the polluting firms possess market power (Heuson 2010). However, this study is restricted to emission standards and taxes, while tradable emission permits are ruled out since market power gives rise to strategic permit trading, which requires some separate effort in investigation. This paper aims at closing this gap and, in doing so, makes three main contributions. First, it provides the first-time full comparative analysis of the three most common pollution control instruments stated above which takes into account two features that are frequently given in actual regulation settings, namely market power of polluting firms and uncertain abatement costs from the regulator's perspective. Second, the paper reveals a new form of strategic permit trading that may arise even though the permit market is perfectly competitive. Finally, the rather pessimistic view concerning the impact of market power on the comparative advantage of tradable emission permits, which dominates in the literature so far, is put into context.

JEL Classification: *D89 · L13 · Q58*
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1 Introduction

There is a long-lasting debate, both in the scientific and political arena, on which of the two fundamental ways of controlling industrial pollutions is preferable in terms of an optimal[1] environmental policy: prices (artificially establishing the non-existent price for pollution, i.e., implementing emission taxes) versus quantities (imposing a direct constraint on emission levels, i.e., implementing emission standards or tradable emission permits). In this respect, the regulator's uncertainty concerning damage and abatement costs, which is virtually a main feature of any real world regulation problem, has triggered special attention. Weitzman (1974) demonstrated in his seminal paper that abatement cost uncertainty makes the pollution control instruments' comparative advantage depending on the relative slopes of the marginal abatement and damage cost function. On the other hand, the regulator's uncertainty with respect to damage costs is irrelevant for the optimal instrument choice. These findings still serve as a benchmark for guiding decisions on the choice of pollution control instruments. For instance, the Academic Advisory Board at the German Federal Ministry of Economics and Technology argued in a recent survey that a global tax on greenhouse gas emissions is preferable to an emission trading system. This is because, among other reasons, industrialised countries, which render the main part of the global abatement effort, face a rather strong increase in marginal abatement costs when reducing emissions, while the associated marginal saving of damage costs tends to be constant (BMWi 2012). Besides political debates, Weitzman's (1974) policy rule similarly attracts considerable attention on the part of science. Up to now, there are various contributions modifying or advancing Weitzman's framework.[2]

A major concern has been put forward by Heuson (2010) in arguing that all these studies have invariably taken it for granted that regulated firms face perfectly competitive markets. By introducing the product market into Weitzman's stochastic framework, he shows, referring to the case of a polluting Cournot oligopoly, that Weitzman's policy rule is biased in the presence of market power. Due to the associated output shortage, standards which ex post turn out to be suboptimally low lead to a more severe increase in aggregate abatement costs, including the loss of consumers' and producers' surplus, compared to the case of perfect competition. Hence, the taxes ability to provide a cap on abatement costs, which is due to the fact that the firms' cost minimisation implies equating abatement costs with the tax rate, takes on greater significance. For this reason, taxes are preferable to standards for a larger range of parameters. Similarly, the adoption of Weitzman's rule in the presence of market power runs the risk of wrongly choosing standards instead of taxes. Obviously, this result is highly relevant for environmental policy making since market power is given in many serious problems of industrial pollution. For instance, consider the carbon dioxide emissions arising from the energy sector, where firms compete, at least locally, à la Cournot (Requate 2005). The main message to be taken away from the policy maker in this respect is that market power (when combined with abatement cost uncertainty) does not only influence the optimal design of pollution control instruments, but also their comparative advantage, which has been neglected so far.

The analysis of Heuson (2010) is somewhat restrictive since it rules out tradable emission permits. This is for the reason that market power gives rise to strategic behaviour of polluting firms in terms of emission trading which affects the permits' comparative advantage and hence requires some separate effort in investigation. However, the increasing attention that

[1] Hereafter, 'optimal' is used synonymously with 'accomplishing the regulator's goal of welfare maximisation' (if applicable subject to market power of the polluting firms and/or uncertainty).

[2] The most important contributions in this respect are given by Tisato (1994), Stavins (1996), Montero (2002), Quirion (2004) and latest Antoniou et al. (2012). For a detailed description of the associated findings see Heuson (2010).

tradable permits attain in environmental policy (e.g. think of the EU Emission Trading System or the upcoming system in China) creates a strong need for understanding how they perform in a setting of market power and uncertain abatement costs compared to standards and taxes. This game theory based paper aims at closing this gap by extending the framework of Heuson (2010) for the instrument of tradable emission permits. The focus is on the case of an asymmetric Cournot duopoly, where firms differ with respect to production costs. In doing so, three main contributions are made. First, the paper provides the first time analysis of the three prevailing pollution control instruments' (emission standards, tradable permits and taxes) comparative advantage, considering both market power of polluting firms and the regulator's uncertainty concerning the firms' abatement costs – two common features given in many environmental policy problems. Second, it demonstrates that permit trading may even be subject to strategic effects when firms behave as permit price takers. Finally, it qualifies the established view in the literature, that market power is detrimental to the performance of tradable emission permits (c.f. Requate 2005).

The paper builds upon a broad literature dealing with polluting firms that engage in various forms of strategic behaviour in terms of emission trading (see Section 2.1 for a detailed review). Clearly, the scope for and type of this behaviour crucially depends on the range of market power. In this respect, two cases are distinguished, whereas the related choices in terms of market structure and permit trade modelling are carefully justified and motivated in Section 2.2. First, it is assumed that the Cournot duopolists face a perfectly competitive permit market. Here, strategic effects may arise in the sense that firms overinvest in permits in order to commit to a more aggressive behaviour in the output market and thus try to gain market share from the rival. The second case grounds on the assumption that the duopolists are the only firms taking part in the permit trade, i.e., market power affects both the product and the (thin) permit market. Thus, the latter comprises a bilateral monopoly and firms trade permits following the Nash bargaining solution. As initially demonstrated by Requate (1993) and Fehr (1993), this allows for using the permit trade as device to coordinate the behaviour in the output market.

How do permits perform compared to standards and taxes within these two settings? On the one hand, the strategic behaviour in the permit market leaves the instruments' trade-off with respect to the handling of uncertainty unaffected, i.e., in this regard, Weitzman's modified "relative-slope-rule" (Heuson 2010) still applies. However, the strategic behaviour has a counter-intuitive impact on abatement efficiency. Provided that the optimal emission level, and thus the total supply of permits, is sufficiently small, strategic permit trading actually boosts the permits' abatement efficiency, i.e., makes them preferable to taxes (which are in turn preferable to standards in any case). This boost is even stronger when market power not only affects the product, but also the permit market. These results can be explained as follows. In case of a perfectly competitive permit market with commitment, the more efficient firm has a stronger incentive to overinvest in permits. This implies a reallocation of permits (and hence of emissions and output) to the firm with lower production costs compared to taxes, thus inducing a lower level of abatement costs (including opportunity costs of abating via output reduction) for any abatement level. This reallocation is reinforced when market power affects both markets and firms trade permits to maximise joint profits (Nash bargaining solution), i.e., they engage in collusive behaviour. Here, contrary to the perfectly competitive permit market, firms internalise the effect of a traded permit on the rival's profit. This provides additional incentives to shift production to the more efficient firm. Of course, for the final choice, both the instruments' trade-off with respect to uncertainty (relative-slope-rule) and abatement efficiency have to be taken into account.

The remainder of the paper is organised as follows. Section 2 reviews the literature on strategic permit trading due to market power (Section 2.1) and motivates the choice of modelling approaches (Section 2.2). Section 3 briefly wraps up the basic model framework of Heuson (2010) which builds the starting point for the further analysis. Section 4 analyses the optimal instrument choice for the benchmark case in which market power solely affects the product market and there is no strategic permit trading. The latter's effects on the instruments' comparative advantage are studied in Section 5 (strategic overinvestment) and 6 (collusive behaviour). Finally, Section 7 concludes.

2 Strategic behaviour in permit trading due to market power

This section gives a brief overview of the literature on strategic effects arising in markets of tradable emission permits due to market power of the regulated firms (Section 2.1).[3] Building upon this, Section 2.2 carefully motivates the respective approaches that have been selected to capture the instrument of tradable permits within this paper. Clearly, the main selection criterion is the approaches' compatibility with the framework provided by Heuson (2010). Moreover, the intention is to gain additional insights by contrasting the two polar cases of a perfectly competitive and a thin permit market (bilateral monopoly).

2.1 Literature review

Naturally, the literature can be organised based on the three constellations of market power concerning the product and permit market since these determine the scope for and possible types of strategic behaviour: market power may either solely affect the product, but not the permit market, and vice versa, or affect both markets.

Imperfectly competitive product market and perfectly competitive permit market

The starting point for this constellation is typically given by several regionally zoned, imperfectly competitive industries which emit the same (global, non-hot-spot) pollutant and are thus pooled in one permit trading system. Provided that the amount of these industries is sufficiently high, firms behave as permit-price-takers, despite having market power within their specific product market. Building upon this setting, Sartzetakis (1997a) considers the case of several symmetric Cournot duopolies with heterogeneous abatement technologies. Due to symmetry, it is sufficient to analyse one (representative) industry while the other 'shadow or numeraire industries' can be neglected. Sartzetakis (1997a) shows that the permit trade involves an inefficient reallocation of shares in the output market which may, contrary to the established view in the literature, outweigh the related saving of abatement costs and thus cause a decrease in welfare – provided that regulator is incompletely informed about damage costs, the firms' costs and demand structure. Sartzetakis (2004) generalises this analysis by assuming both heterogeneous abatement and production technologies. Strictly speaking, however, the aforesaid reallocation

[3] Since the goal of this paper is to extend the static game theory framework of Heuson (2010), dynamic studies on tradable permits (e.g. Hagem and Westskog 1998) are neglected in what follows. The same holds true for studies focusing on specific topics going beyond the mere (welfare) effects of the permit instrument, such as incentives for technological innovation (Montero 2002a; Montero 2002b; Fischer et al. 2003), problems of monitoring and enforcement (van Egteren and Weber 1996; Malik 2002; Chavez and Stanlund 2003), or lobbying efforts for taking influence on the allocation of permits (Long and Soubeyran 1998).

effect does not occur for strategic reasons. It is rather due to the fact, that the relatively more inefficient firm, i.e. the firm with higher marginal abatement costs, has a higher marginal willingness to pay concerning emission permits and thus behaves more 'aggressively' in the permit market.[4] Seeing that the permit market is perfectly competitive, it indeed seems natural that there is no scope for strategic behaviour. Nevertheless, the theory of strategic environmental policy suggests that still some strategic effects may occur for the following reason. Ulph (1996) demonstrates that regulated polluting firms with market power have an incentive to overinvest in abatement technologies and capacity, respectively, which is detrimental from a (global) welfare perspective. In this way, the firms can commit to a more aggressive behaviour in the product market. Their increased abatement capacity serves as a credible signal for being capable of producing more at any given level of environmental regulation, which they intend to make use of for gaining market share from their rivals. Obviously, tradable emission permits similarly increase a firm's production capacity and thus might be used as commitment device for gaining market share as well. It is important to see that the commitment only works given that the permit endowment cannot be easily changed, otherwise the signal lacks credibility. While the investment in abatement capacity in case of Ulph (1996) clearly fulfils the requirement of being hardly alterable, this is not straightforward to see for the permit endowment at first glance. However, some seminal contributions suggest that this might indeed be the case. Fehr (1993) argues that a non-existing or malfunctioning secondary market, transaction costs associated with permit trading or, referring to Hahn (1989), a firm's reservation in trading permits with a direct competitor, can support the credible signalling arising from the initial permit endowment. Thus, it is reasonable to assume that cases do exist where firms engage in strategic behaviour, or rather strategic permit overinvestment, despite the permit market is perfectly competitive. This issue, which has been neglected by the literature so far,[5] will be analysed in detail in Section 5.

Perfectly competitive product market and imperfectly competitive permit market

The seminal work of Hahn (1984) implicitly refers to this constellation by neglecting the output market and considering a dominant firm with competitive fringe in the permit market. Similarly to a monopolist (monopsonist), the dominant firm shortens its permit supply (demand) when being in a selling (buying) position in order to raise (reduce) the equilibrium permit price. Later on, this behaviour has been labelled as cost-minimising manipulation of the permit price (Misiolek and Elder 1989). In a recent study, Malueg and Yates (2009) reveal the origin of this constellation, which is given by local pollution problems. Since the nature of these problems calls for geographically restricted permit trading in order to avoid hot spot effects, the permit market is likely to be imperfectly competitive. This may go well together with perfect competition in the output market, given that regulated firms of many regions or countries join the latter. Malueg and Yates (2009) consider a thin permit market, i.e. firms constitute a bilateral oligopoly, whereas the associated equilibrium is determined through the supply function approach.[6] It is shown that, similarly to Hahn (1984), firms engage in cost-minimising manipulation of the permit price. However, the related welfare-decreasing affects are attenuated when firms possess

[4] This reallocation effect similarly occurs in case of emission taxes, as has been demonstrated by Simpson (1995).
[5] Admittedly, Fehr (1993) reveals the possibility of strategic overinvestment in emission permits. However, he takes for granted that firms can influence the permit price.
[6] The supply function approach is, besides the Nash bargaining solution (see below), a concept for identifying equilibria in case of a bilateral oligopoly. The basic idea is that firms submit a net supply of permits, more precisely, a supply function stating the desired trade volume for a given permit price, to the market maker who in turn determines the market-clearing price.

private information on their abatement costs and thus strategically misreport the related cost parameters to the regulator.

Imperfectly competitive product and permit market

Clearly, the largest scope for strategic behaviour is given when market power affects both the product and the permit market,[7] since not only the options of making use of market power from the two constellations depicted above persist, but rather new options arise. Misiolek and Elder (1989) extend Hahn's (1984) framework by assuming that the dominant firm's position also pertains to the output market. Consequently, through increasing its demand for permits, the dominant firm can pointedly raise the costs of the competitive fringe (raising rivals' costs strategies)[8] and thus reinforce its position (positioning strategies), or even create barriers to potential entrants (exclusionary manipulation). Sartzetakis (1997b) also deals with raising rivals' costs strategies, however within a different framework. He takes for granted a Cournot duopoly, where one of the firms takes the position of the Stackelberg leader in the permit market and thus can increase the follower's costs by manipulating the permit price. The associated welfare impacts crucially depend on the leader's and follower's relative efficiency in terms of production costs. Besides raising rivals' costs strategies, constellations of double market power may ensue an implicit collusion with respect to the output level, as shown by Fehr (1993), Requate (1993) and Fershtman and Zeeuw (1995) for the case of a Cournot duopoly, each with assuming different framework conditions in terms of the firms' production and abatement technologies. The basic idea is that the duopolists – being the only firms to take part in the permit market – coordinate their behaviour on the product market beyond the control mechanisms of antitrust authorities through establishing a specific allocation of permits, which may, as argued above, serve as commitment device. In terms of cooperative game theory, the firms simply adopt the Nash (1950) bargaining solution in order to maximise joint profits. Here it is important to see that the related 'contracts' may only comprise the volume of traded permits and associated side-payments, but must not be conditioned on output levels, since otherwise antitrust authorities would intervene (Fershtman and Zeeuw 1995, p. 5). Finally, Fehr (1993) also points to the possibility of strategic permit overinvestment in case of double market power. However, the nature and impact of this behaviour fully corresponds to strategic overinvestment when market power solely affects the output market (see above).

2.2 Selection of modelling approaches

The basic intention of this paper is to extend the analysis of Heuson (2010) for the case of tradable emission permits in order to study their comparative advantage in a setting with market power and uncertainty. For this reason, the main selection criterion is that the approaches for capturing strategic behaviour in permit markets depicted above are consistent with the framework of Heuson (2010) and Weitzman (1974), respectively. In particular, consistency in this respect most notably refers to the following features. First, the type of competition in the output market is that of Cournot. Second, in terms of the information structure, the regulator is uncer-

[7] Market power affects both markets provided that the firms taking part in the product market (which is subject to market power) are the only ones taking part in the permit market or permit trading involves several industries (subject to market power), but the total number of firms is too low to guarantee price-taking behaviour in the permit market.

[8] It should be noted that raising rivals' costs strategies not only imply market power in the permit market (which is necessary for influencing the permit price), but also in the product market, since there is no way that changes in the permit price benefit a firm acting as price-taker in the output market (Misiolek and Elder 1989, p. 160).

tain about the firms' abatement costs, but there is no scope for problems of asymmetric information. Finally, the regulator's goal is to achieve Pareto-Optimality (subject to uncertainty and market power).

So which of the approaches presented in Section 2.1 are basically consistent with these requirements? Obviously, all contributions grounding on the assumption of a perfectly competitive output market, i.e. Hahn (1984) as well as Malueg and Yates (2009), can be ruled out from the beginning. In terms of the constellation of an imperfectly competitive product and perfectly competitive permit market, all approaches basically qualify. However, as stated in Section 2.1, the reallocation affect analysed in Sartzetakis (1997a and 2004) is not of strategic nature and similarly occurs in case of emission taxes. Nevertheless, the related constellation (Cournot duopolists which take the permit price as exogenously given) will serve as a benchmark for comparing and highlighting the impact of 'real' strategic behaviour (see Section 4). Such behaviour is actually given by the overinvestment in permits for reasons of commitment, which can be modelled along the lines of Ulph (1996). In each case – benchmark setting referring to Sartzetakis (1997a and 2004) and overinvestment approach according to Ulph (1996) – consistency implies to assume, like for instance Sartzetakis (1997a) does, that all the shadow or numeraire industries are identical to the Cournot duopoly under consideration. Otherwise, the regulator could not achieve the constrained Pareto-Optimum with the instruments at hand (Heuson (2010) and Weitzman (1974) presume uniform emission standards and taxes), which in turn would infringe on the requirement above. Referring to the case of double market power, the approach of Misiolek and Elder (1989) lacks compatibility since they consider a dominant firm with competitive fringe in the output market. Sartzetakis (1997b) constructs a raising rivals costs scenario based on the assumption that one of the Cournot-duopolists (playing Nash in the output market) takes the role of the Stackelberg leader in the permit market and fixes the permit price. Since this proceeding can hardly be motivated and moreover puts the games solvability at risk – an additional sequence had to be introduced – it will be neglected in what follows. On the contrary, the collusion approach offered by Fehr (1993), Requate (1993) and Fershtman and Zeeuw (1995), which takes for granted a bilateral duopoly both in the permit and the output market, not only offers promising insights but also fulfils all the consistency requirements.[9] Finally, the case of strategic overinvestment can also be analysed in a setting of double market power, as suggested by Fehr (1993). However, the following treatises abstain from this exercise for two reasons. On the one hand, this leads to some technical complications in terms of consistency.[10] On the other hand, the nature and impacts of the overinvestment behaviour is similar to the one occurring in the setting of a perfectly competitive permit and imperfectly competitive output market, for which reason a separate analysis promises no fundamentally new insights.

To sum up, three different settings will be considered in what follows in order to study the tradable permits' comparative advantage in case of market power and regulatory uncertainty with

[9] Note that this constellation (double bilateral duopoly) could also be solved with the supply function approach following Malueg and Yates (2009). However, the associated reporting of supply functions to the regulator would necessarily comprise the firms' private information on abatement costs and thus give rise to problems of asymmetric information, which in turn violates the information structure taken for granted in Heuson (2010) and Weitzman (1974), respectively.

[10] Clearly, strategic overinvestment cannot occur within a cooperative setting, for which reason the Nash bargaining solution cannot be considered as solution concept. Similarly, the supply function approach has to be ruled out since it involves problems of asymmetric information as explained above. Thus, the only possible approach remaining is that of an elastic permit supply and thus an influenceable permit price within the industry under consideration, as suggested by Fehr (1993). From the viewpoint of a single duopolistic industry, the elasticity of the permit supply requires permits being shifted to or from other (shadow) industries. However, due to the industries' symmetry, which has to be assumed for the reasons stated above, will not come about – in case one industry has an incentive to buy/sell permits, the same applies to all other industries, and the incentive will blow out. Thus, there is no way of meeting the consistency requirements for the overinvestment approach within a setting of double market power.

respect to abatement costs. The combination of a perfectly competitive permit market and a Cournot duopoly, not giving rise to any strategic behaviour, will serve as a benchmark (Section 4). In a further step, scope for commitment is introduced, leading to strategic overinvestment (Section 5). Finally, market power is assumed to affect both markets, resulting in collusive behaviour (Section 6). Naturally, all these approaches have to be fitted into the specific model framework of Heuson (2010). As will be seen, contrary to the established view in the literature, market power can indeed improve the permit instrument's performance, provided that the optimal emission level is sufficiently low.

3 The basic model framework

This section briefly resumes the model framework of Heuson (2010) which provides the basis for the further analysis.[11] Moreover, the results of the comparative analysis of instruments for the case of perfect competition in each market are outlined. Basically, the framework can be borrowed without any changes. Nevertheless, the following two small adjustments are made. First, the focus is on the case of asymmetric firms from the beginning, since otherwise the firms' strategic behaviour would have no impact on the permits' comparative advantage. Second, for the sake of simplicity and without loss of generality, the analysis restricts to the case of two firms, i.e. a Cournot duopoly is considered rather than an oligopoly.

Two firms $i = 1,2$ each produce x_i units of a homogenous good at costs $c_{pi}(x_i) = V_i x_i + (v/2)x_i^2$, where $V_1 < V_2$, i.e., marginal production costs of the low cost firm $i = 1$ run parallel below those of the high cost firm $i = 2$. Total output is given by $X = x_1 + x_2$. Each unit produced causes one unit of emissions. The latter can be abated either by output shortage or by adopting an end-of-pipe abatement technology, which allows for reducing emissions without altering the production level. Thus, the firms' individual emission level is given by $em_i(x_i, a_{ei}) = x_i - a_{ei}$, a_{ei} denoting the end-of-pipe abatement effort. The costs associated with the latter follow the function $c_e(a_{ei}, \theta) = (Z + \theta)a_{ei} + (z/2)a_{ei}^2$. End-of-pipe costs are perfectly known by the firms, but comprise, from the regulator's perspective, a stochastic element θ with familiar density $dF(\theta)$. Without loss of generality it is assumed that $E[\theta] = 0$ and thus $Var[\theta] = E[\theta^2]$. Consumers are assumed to have quasi-linear preferences, leading to the linear inverse demand function $p(X) = B - bx$. Finally, the monetary damage caused by the firms' emissions is captured by $C_D(EM) = DEM + (d/2)EM^2$, where $EM = em_1 + em_2$. Note that except for θ, the regulator is fully informed about all the functions mentioned as well as the firms' emission levels.

The timing of environmental regulation follows a Stackelberg structure. In the first stage, the regulator chooses to implement one of the instruments at hand – uniform emission standards, tradable emission permits or uniform emission taxes – in order to maximise expected welfare or, equivalently (Heuson 2010, p. 353), to minimise the sum of expected aggregate abatement and damage costs. In the second stage, firms fix their profit-maximising output and end-of-pipe levels, given the respective environmental regulation.

Moreover, it is important to note that the analysis is restricted to the interior solution, according to which all firms render strictly positive output and end-of-pipe abatement levels in the sub-

11 In what follows, only the essential components of the model will be introduced. For a detailed explanation and justification of the framework see Heuson (2010).

game perfect equilibrium. This in turn requires the optimal emission level to be sufficiently (but not too) low.[12]

The optimal instrument choice in case of perfect competition on both markets is straightforward to determine, since it directly follows from Heuson (2010).[13] The instruments' comparative advantage consists of two components, namely abatement efficiency and the uncertainty-related trade-off between price- and quantity-based instruments which was initially analysed by Weitzman (1974). In terms of abatement efficiency, taxes and tradable permits similarly succeed in enforcing a giving emission level at minimal abatement costs because they both create a uniform price for emissions and thus guarantee that the firms' marginal abatement costs – which, due to perfect competition, are congruent to the respective societal costs – are balanced. However, exactly the opposite is true for uniform emissions standards since these do not account for the discrepancies in the firms' costs and are thus clearly inferior to taxes and tradable permits with respect to abatement efficiency (c.f. Tisato 1994). In terms of the uncertainty-related trade-off, standards and permits are equivalent and should be preferred to taxes when marginal damage costs run steeper than aggregate marginal abatement costs, and vice versa (Weitzman 1974). Considering both abatement efficiency and the uncertainty-related trade-off obviously suggests that tradable permits are always favourable to standards, while the optimal choice between permits and taxes follows Weitzman's relative-slope-rule mentioned before. However, these results cannot be maintained when market power is introduced, as will be seen from the following sections.

4 Introducing market power for the benchmark case of no strategic behaviour

This section analyses the optimal instrument choice for the case of an asymmetric Cournot duopoly in the output market, whereas the duopolists take the permit price as exogenously given (Section 4.1). On this basis, an investigation of the instruments' comparative advantage is provided in Section 4.2. As stated above, the price taking behaviour arises when a sufficient amount of duopolistic industries coexist which are all pooled in one permit market, such that the latter is perfectly competitive. Since all industries are assumed to be symmetric, the optimal instrument choice can be determined by analysing one (representative) industry. Taking for granted that the firms' permit endowments cannot be used as a commitment device,[14] any strategic behaviour is ruled out. The results serve as benchmark to enable a better understanding of the strategic behaviour's impact on the instruments' comparative advantage, which will be dealt with in Sections 5 and 6.

4.1 Optimal instrument choice

Solving the Stackelberg regulation game with backwards induction implies that stage two has to be analysed first. In case of uniform emission standards, the firms maximise profits subject to the constraint that their emissions must not exceed the level s:

[12] The underlying reason for this requirement is that marginal end-of-pipe abatement costs are positive ($Z + \theta > 0$) in case of zero abatement (on the contrary, marginal costs of abatement via output shortage are zero in this case). Thus, the end-of-pipe abatement option is only used when the overall abatement load (emission level) is sufficiently high (low). Similarly, a too low optimal emission level is inappropriate as well since it might involve that firms cease producing. For more details, see Heuson (2010).

[13] The formal proof can be obtained from the author upon request.

[14] As stated above, this implies that the initial permit endowment can be changed easily (see Section 2.1).

$$\max_{\{x_i,a_{ei}\}} \pi_i(x_i, a_{ei}, \theta) = p(X)\, x_i - c_{pi}(x_i) - c_e(a_{ei}, \theta)\; s.t.\, em_i(x_i, a_{ei}) \leq s \tag{1}$$

Profit maximisation necessarily implies the constraint to be binding, for which reason the related first order condition reads

$$\partial\left(p(X)x_i - c_{pi}(x_i)\right)/\partial x_i = \partial c_e(a_{ei}, \theta)/\partial a_{ei}|_{a_{ei}=x_i-s} \tag{2}$$

Since firms have two abatement options available, namely output shortage and end-of-pipe, (2) simply states that the associated marginal costs – the loss of profit due to producing (and thus emitting) one marginal unit less and the additional costs due to raising the end-of-pipe abatement effort for one marginal unit – have to be balanced. Solving (2) for both $i = 1{,}2$ simultaneously gives the Cournot Nash equilibrium allocation (c.f. Heuson 2010):

$$x_i(s, \theta) = \frac{1}{2}\left(\frac{2B - 2(Z+\theta) - V_1 - V_2}{3b+z+v} - \frac{V_i - V_{-i}}{b+z+v}\right) + \frac{z}{3b+z+v}s,$$
$$a_{ei}(s, \theta) = x_i(s, \theta) - s,\, em_i(s) = s \tag{3}$$

Clearly, by implementing emission standards, the regulator can perfectly control the firms' emission levels despite her lack of information. However, due to the latter, she cannot foresee how firms split their total abatement burden between the two options, i.e. both the equilibrium output and end-of-pipe abatement levels are random from her perspective. In case of emission taxes, firms face an additional cost component given by the rate t charged per emission unit actually discharged into the environment, which results in the following maximisation problem

$$\max_{\{x_i,a_{ei}\}} \pi_i(x_i, a_{ei}, \theta, t) = p(X)\, x_i - c_{pi}(x_i) - c_e(a_{ei}, \theta) - t em_i(x_i, a_{ei}) \tag{4}$$

and the familiar first order condition

$$\partial\left(p(X)x_i - c_{pi}(x_i)\right)/\partial x_i = t = \partial c_e(a_{ei}, \theta)/\partial a_{ei}. \tag{5}$$

Contrary to standards, firms fix the output and end-of-pipe level independently of each other (by equating the respective marginal costs to the tax rate), since there is no constraint to be taken into account. Consequently, within the Cournot Nash equilibrium choices, the regulator's uncertainty does not affect the output level. However, the opposite is true for the end-of-pipe and thus as well the emission level:

$$x_i(t) = \frac{1}{2}\left(\frac{2B - V_1 - V_2}{3b+v} - \frac{V_i - V_{-i}}{b+v}\right) - \frac{1}{3b+v}t,\, a_{ei}(t, \theta) = \frac{t - Z - \theta}{z},\, em_i(t, \theta) = x_i(t) - a_{ei}(t, \theta) \tag{6}$$

Determining the Cournot Nash equilibrium in case of tradable permits comprises two steps since, strictly speaking, two permit markets are involved. The transfer of permits from the regulator to the firms occurs in the primary market, resulting in the initial permit endowment $q_{i=1,2}$. Afterwards, firms are allowed to trade permits at a given price w in the secondary market. Backwards induction requires starting with the latter, i.e., firms maximise profits, taking into account the transfer payment associated with the permit trade, $w(em_i(x_i, a_{ei}) - q_i)$[15]

[15] For the sake of simplicity, assume that one permit just covers one unit of emissions.

$$\max_{\{x_i,a_{ei}\}} \pi_i(x_i,a_{ei},\theta,t) = p(X)\,x_i - c_{pi}(x_i) - c_e(a_{ei},\theta) - w(em_i(x_i,a_{ei}) - q_i) \quad (7)$$

In this respect, firms may either take the position of a buyer, provided that their emission level exceeds the initial permit endowment, $em_i(x_i,a_{ei}) > q_i$, or that of a seller in the opposite case. Obviously,q_i is completely irrelevant to the solution of (7). Thus, the secondary market Cournot Nash equilibrium perfectly coincides with the one given in the tax regime (6), whereas w substitutes t – this holds true independently of the allocation mode chosen in the primary market, such as grandfathering or auctioning. The equilibrium emission level $em_i(w,\theta) = x_i(w) - a_{ei}(w,\theta)$ similarly reflects the firms' demand for emission permits in the primary market $l_i(w,\theta)$. The equilibrium in the latter is characterised by the permit price $w^*(L,\theta)$ which brings in line the total (inelastic) permit supply and the total permit demands, i.e. $L = l_1(w,\theta) + l_2(w,\theta)$:[16]

$$w^*(L,\theta) = \frac{z(2B-V_1-V_2)+2(Z+\theta)(2b+v)}{2(2b+z+v)} - \frac{z(2b+v)}{2(2b+z+v)}L \quad (8)$$

Plugging (8) into (6), whereas t is substituted by w, yields the Cournot Nash equilibrium allocation as a function of the permit supply L:

$$x_i(L,\theta) = \frac{1}{2}\left(\frac{2B-2(Z+\theta)-V_1-V_2}{2b+z+v} - \frac{V_i-V_{-i}}{v}\right) + \left(\frac{z}{2b+z+v}\right)\frac{L}{2},$$
$$a_{ei}(L,\theta) = x_i(L,\theta) - l_i(L), \quad l_i(L) = em_i(L) = \frac{L}{2} - \frac{V_i-V_{-i}}{v} \quad (9)$$

Clearly, as tradable permits are a quantity based instrument like emission standards, the regulator is capable of exactly controlling the firms' emissions despite her lack of information for perfectly analogous reasoning.

In stage one, the regulator chooses s, t and L, respectively, such that the expectation of total costs , i.e. the sum of aggregate abatement and damage costs,

$$TC(\boldsymbol{x},\boldsymbol{a_{ei}}) = AC(\boldsymbol{x},\boldsymbol{a_{ei}}) + C_D(EM), \quad (10)$$

is minimised, where

$$AC(\boldsymbol{x},\boldsymbol{a_{ei}}) = \left(\int_0^{X^0} p(X)dX - \sum_i c_{pi}(x_i^0)\right) - \left(\int_0^{X} p(X)dX - \sum_i c_{pi}(x_i)\right) + \sum_i c_e(a_{ei}) \quad (11)$$

i.e., the aggregate abatement costs comprise both the total loss of consumers' and producers' surplus due to abatement via output shortage and total and end-of-pipe abatement costs. In doing so, the regulator anticipates the respective allocation of the regulated Cournot Nash equilibrium in stage two, i.e., (3), (6) and (9) respectively. The related first order condition in case of standards prescribes to bring in line the expectation of aggregate marginal abatement costs and marginal damage costs, in each case related to an infinitesimal increase in s:

$$E\left[p(X(s,\theta))\frac{\partial X(s,\theta)}{\partial s} - \sum_i \frac{c_{pi}(x_i(s,\theta))}{\partial x_i(s,\theta)}\frac{\partial x_i(s,\theta)}{\partial s} - \sum_i \frac{c_e(a_{ei}(s,\theta))}{\partial a_{ei}(s,\theta)}\frac{\partial a_{ei}(s,\theta)}{\partial s}\right] = \frac{\partial C_D(2s)}{\partial s} \quad (12)$$

[16] Strictly speaking, L is not the total supply of permits, but rather the supply that is allocated to one specific (shadow) industry. Since, however, all (shadow) industries are symmetric by assumption this subtlety can be neglected.

The related first order conditions for taxes and permits can be calculated perfectly analogously. Solving these conditions yields the optimal standard s^*, tax rate t^* and permit supply L^*, where $L^* = 2s^*$.[17] It is natural to define the comparative advantage of a pair of instruments as the ex ante expected difference in total costs generated by the optimal manifestations of these instruments. The comparative advantage of permits over standards, permits over taxes and standards over taxes, reads in each case

$$\begin{aligned}\Delta(L^*, s^*) &= E[TC(\boldsymbol{x}(s^*,\theta), \boldsymbol{a_e}(s^*,\theta),\theta) - TC(\boldsymbol{x}(L^*,\theta), \boldsymbol{a_e}(L^*,\theta),\theta)] \\ &= \Delta AC(s^*, L^*),\end{aligned}$$

$$\begin{aligned}\Delta(L^*, t^*) &= E[TC(\boldsymbol{x}(t^*), \boldsymbol{a_e}(t^*,\theta),\theta) - TC(\boldsymbol{x}(L^*,\theta), \boldsymbol{a_e}(L^*,\theta),\theta)] \\ &= 2Var[\theta]\left(\frac{d-\alpha}{z^2}\right),\end{aligned}$$

$$\begin{aligned}\Delta(s^*, t^*) &= E[TC(\boldsymbol{x}(t^*), \boldsymbol{a_e}(t^*,\theta),\theta) - TC(\boldsymbol{x}(s^*,\theta), \boldsymbol{a_e}(s^*,\theta),\theta)] \\ &= 2Var[\theta]\left(\frac{d-\alpha}{z^2}\right) - \Delta AC(s^*, t^*),\end{aligned}$$

where $\alpha = \frac{z\left(9b^2+2bz+6bv+v(v+z)\right)}{2(3b+z+v)^2} > 0$, $\Delta AC(s^*, t^*) = \Delta AC(s^*, L^*) = \frac{z(V_2-V_1)^2}{4v(v+z)} > 0$. (13)

From this follows

Proposition 1 *The optimal choice between tradable emission permits, emission standards and taxes for regulating a polluting Cournot duopoly with price taking behaviour on the permit market obeys the following policy rule:*

(i) Permits should be preferred to standards in any case since $\Delta(L^*, s^*) = \Delta AC(L^*, s^*) > 0$.

(ii) Permits should be preferred to taxes if and only if $\Delta(L^*, t^*) > 0 \Leftrightarrow d > \alpha$.

(iii) Standards should be preferred to taxes if and only if $\Delta(s^*, t^*) > 0 \Leftrightarrow 2Var[\theta]\left(\frac{d-\alpha}{z^2}\right) > \Delta AC(s^*, t^*) \Leftrightarrow d > \frac{z^2 \Delta AC(s^*,t^*)}{2Var[\theta]} + \alpha$, *provided that the instrument of tradable emission permits is not available for some reason.*

4.2 Examining the instruments' comparative advantage

As can be seen from (13), the instruments comparative advantage basically comprises two components. On the one hand, $2Var[\theta]\left(\frac{d-\alpha}{z^2}\right)$ depicts the well-known trade-off related to abatement cost uncertainty between price and quantity based instruments. Standards and permits allow for a full control of the firms' emissions and thus guarantee a deterministic damage cost level, against what they entail uncertain abatement costs from the regulator's perspective. The opposite is true for taxes, which put a cap on abatement costs since firms equate their marginal abatement costs with the tax rate. However, this necessarily involves an uncertain emission and hence damage cost level. The quantity based instruments' characteristics turn out to be more beneficial than those of the price based when damage costs respond more sensitively to uncertainty caused discrepancies between the optimal and the actually enforced emission level, i.e., when marginal damage costs run steeper than aggregate marginal abatement costs ($d > \alpha$). Taxes should be preferred in the opposite case for analogous reasons. In this respect, a brief

[17] The explicit calculation of s^*, t^* and L^* is straightforward but yields tedious expressions without any further insights and is thus omitted. This similarly applies to all subsequent sections.

remark concerning the market power's impact on this trade-off, which has been revealed by Heuson (2010), is due. Contrary to Weitzman (1974) who implicitly assumes polluting industries with perfect competition, all instruments equally fail to achieve a given abatement or emission level at minimal aggregate abatement costs. This is for the reason that market power entails a discrepancy between the marginal costs of abatement via output shortage from the social (marginal loss of consumers' and producers' surplus, $p(X) - \partial c_{pi}(x_i)/\partial x_i$) and the firm perspective (marginal loss of profit, $\partial \left(p(X)x_i - c_{pi}(x_i) \right) / \partial x_i$), which does not exist in case of perfect competition. More precisely, the related marginal costs are lower on the firms' level for any x_i, i.e.

$$p(X) - \frac{\partial c_{pi}(x_i)}{\partial x_i} > \frac{\partial \left(p(X)x_i - c_{pi}(x_i) \right)}{\partial x_i}, \quad (14)$$ [18]

since a duopolists can use its market power to shift a part of the output shortage costs to consumers by increasing the price. Consequently, market power induces firms to choose, from a social perspective, an inefficient mix of abatement options: firms render a suboptimally high share of their abatement burden via output shortage and an inefficiently low share via end-of-pipe. Thus, the aggregate marginal abatement cost function realisable in case of market power runs steeper compared to the minimised marginal abatement cost function given in case of perfect competition ($\alpha > \alpha^{min}$). This reflects that the taxes' comparative advantage gains due to market power which is simply for the reason that the taxes' capability of putting a cap on abatement costs – including the loss of consumers' and producers' surplus – becomes more important in terms of limiting the detrimental effects of excessive abatement via output shortage.[19]

The second component in the coefficient of comparative advantage, $\Delta AC(s^*, t^*) = \Delta AC(s^*, L^*)$, stems from the fact, that the instruments perform differently with respect to the efficient allocation of abatement efforts between firms.[20] Uniform standards are well known to produce an inefficient allocation (Tisato 1994): They prescribe the same emission level to both firms and thus impose a higher abatement burden on the more efficient firm ($i = 1$), which produces more in the unregulated equilibrium. Therefore, marginal abatement costs of the latter are higher than those of $i = 2$ (both from the firm and social perspective). On the contrary, tradable permits and taxes create a unique price for emissions and thus imply that, compared to standards, the total abatement burden is reallocated in favour of $i = 1$ since this firm has a higher marginal willingness to pay for (tradable) emission rights. Against this background, $\Delta AC(s^*, t^*) = \Delta AC(s^*, L^*)$ reflect the standards' excess in aggregate abatement costs compared to taxes and tradable permits.[21] However, form the social perspective, still the abatement allocation produced by L^* and t^* is not efficient. Since firms bring in line the price for emissions with their individual, rather than with the social marginal abatement costs, see (14), we have

[18] For the proof see Heuson (2010).

[19] The calculation of both the realisable and the minimised aggregate (marginal) abatement cost function can be taken from Heuson (2010).

[20] This should not be mixed with the fact that, as stated before, all the instruments equally involve an inefficient mix of the two abatement options within each firm.

[21] Note that this excess is constant for any given overall abatement level induced by the respective instruments (Heuson 2010).

$$\left(\left(p(X) - \frac{\partial c_{p1}(x_1)}{\partial x_i}\right) - \left(p(X) - \frac{\partial c_{p2}(x_2)}{\partial x_2}\right)\right)\Bigg|_{\boldsymbol{x}=\boldsymbol{x}(L^*,\theta)} =$$

$$\left(\left(p(X) - \frac{\partial c_{p1}(x_1)}{\partial x_i}\right) - \left(p(X) - \frac{\partial c_{p2}(x_2)}{\partial x_2}\right)\right)\Bigg|_{\boldsymbol{x}=\boldsymbol{x}(t^*)} = \frac{b(V_2 - V_1)(b+v)}{b^2 + 2bv + v(z+v)} > 0 \tag{15}$$

Thus, in terms of abatement efficiency, firm 1 produces (abates) too less (too much), while the opposite is true for firm 2.

Taking uncertainty related trade-off and abatement efficiency together, it is clear that standards should be ruled out from the beginning – provided that the instrument of tradable permits is available. The choice between permits and taxes solely depends on the uncertainty related trade-off. However, care has to be taken, since the modified slope rule developed by Heuson (2010) has to be applied rather than the original policy rule by Weitzman (1974). Otherwise, the regulator runs the risk of wrongly choosing quantities instead of prices.

In the following sections, the impact of the firms' strategic behaviour in the permit market is studied. As will be seen, this behaviour solely affects the instruments' comparative advantage in terms of abatement efficiency, while the uncertainty related trade-off remains unchanged.

5 Strategic overinvestment in emission permits

This section sticks to the previous constellation of market power, i.e. the Cournot duopolists take the permit price as exogenously given. However, contrary to Section 4, we argue along the lines of Ulph (1996) that even emission permits traded in markets subject to price taking behaviour may give rise to strategic behaviour. Particularly, permits, since determining a firm's production capacity, may be used as a device for committing to a more aggressive behaviour in the output market in order to gain market share from its rivals. Such commitment implies that the permit endowment cannot be easily changed in the secondary market, e.g. due to transaction costs associated with the trade (Fehr 1993) or since firms might refuse to transfer permits to a direct competitor (Hahn 1989). In what follows, the impact of the resulting strategic overinvestment in permits is studied. For obvious reasons, the performance of standards and taxes perfectly coincides with the results derived in Section 4 and thus needs not to be investigated anew.

5.1 Optimal instrument choice

In case of commitment, the sequential game of determining the optimal permit supply entails an additional stage compared to Section 4.1. Since firms anticipate the impact of their permit endowment on the output market equilibrium, the (net) permit demand, the output and the end-of-pipe abatement levels are no longer fixed simultaneously. Rather, the permit trade in the secondary market occurs before the interaction in the output market. Thus, in total, the game comprises three stages. Starting with the final stage, firms fix x_i and a_{ei} given the constraint that their emission level must not exceed their permit endowment resulting from the secondary market equilibrium l_i. Obviously, this problem is perfectly analogous to a regulation via standards, (1). Taking into account that firms however face an individual cap on emissions (l_i) rather than a uniform one (s), the output market equilibrium reads

$$x_i(l_1, l_2, \theta) = \frac{1}{2}\left(\frac{2B - V_1 - V_2 + z(l_1 + l_2) - 2(Z + \theta)}{3b + z + v} + \frac{V_{-i} - V_i + z(l_i - l_{-i})}{b + z + v}\right),$$
$$a_{ei}(l_1, l_2, \theta) = x_i(l_1, l_2, \theta) - l_i, em_i(l_i) = l_i \quad (16)$$

In the secondary market, firms trade permits such that their profit resulting from (16) is maximised – including revenues from selling permits ($l_i < q_i$) or expenses from buying permits ($l_i > q_i$):

$$\max_{l_i} \pi_i(l_1, l_2, \theta) - w(l_i - q_i),$$

where $\pi_i(l_1, l_2, \theta) = \pi_i(\boldsymbol{x}(l_1, l_2, \theta), \boldsymbol{a_e}(l_1, l_2, \theta), \theta)$ (17)

The related first order condition states that the marginal profit of the last traded permit shall equal the associated revenue or expenses stemming from the permit trade, or, to put it differently, the marginal willingness to pay for permits and the permit price have to balanced:

$$\frac{\partial \pi_i(l_1,l_2,\theta)}{\partial l_i} = \frac{\partial \pi_i(\cdot)}{\partial x_i(l_1,l_2,\theta)} \frac{\partial x_i(l_1,l_2,\theta)}{\partial l_i} + \frac{\partial \pi_i(\cdot)}{\partial a_{ei}(l_1,l_2,\theta)} \frac{\partial a_{ei}(l_1,l_2,\theta)}{\partial l_i} + \frac{\partial \pi_i(\cdot)}{\partial x_{-i}(l_1,l_2,\theta)} \frac{\partial x_{-i}(l_1,l_2,\theta)}{\partial l_i} = w \quad (18)$$

Given the Cournot conjecture, the duopolists are well aware of being able to influence the equilibrium price with their output decision. Consequently, contrary to the case without commitment (Section 4.1), they do not only consider their permit endowments' influence on own profit. Rather, they take into account the indirect effect on the rival's output level as well: a purchase of additional permits increases a firm's capacity for emissions and, similarly, output. Provided the amount of permits held tends to be rigid, a firm can credibly commit itself to a more aggressive behaviour in the output market, i.e. to a larger output level, in this way. Figure 1 illustrates this effect of strategic overinvestment in emission permits exemplary for the case that firm $i = 1$ raises its permit endowment from l_1 to $\hat{l}_1$:

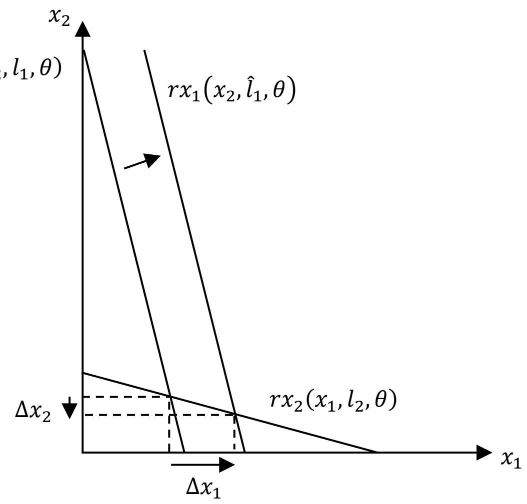

Figure 1: Strategic overinvestment in permits (exemplary for firm $i = 1$, where $\hat{l}_1 > l_1$)[22]

This increase in permits leads to a parallel outwards shift of the output reaction function of firm 1, $rx_1(x_2, l_1, \theta)$, reflecting that firm 1's best response to any output level of firm 2 exceeds the

[22] The derivation of the output reaction functions and the formal proof for their characteristics is provided in Appendix 1.

one in case of l_1 for a constant amount. In order to counter the resulting price decline, firm 2 is forced to curb its production activity. Consequently, the Cournot Nash equilibrium subject to strategic overinvestment of firm 1 (intersection of $rx_1(x_2, \hat{l}_1, \theta)$ and $rx_2(x_1, l_2, \theta)$) is characterised by a reallocation of market shares in favour of firm 1 ($\Delta x_1 > 0, \Delta x_2 < 0$), compared to the initial equilibrium (intersection of $rx_1(x_2, l_1, \theta)$ and $rx_2(x_1, l_2, \theta)$). Obviously, this entails an increase in the firm 1's profit, i.e., $\frac{\partial \pi_1(\cdot)}{\partial x_2(\cdot)} \frac{\partial x_2(\cdot)}{\partial l_1} > 0$, see (18).

This can be summed up to

Proposition 2 *Provided that emission permits fulfil the commitment function described above, permit price taking Cournot duopolists engage in strategic permit overinvestment in order to gain market share from their rival, i.e., the permit demand arising from the secondary market exceeds the one given in the absence of commitment, $\bar{l}_i(w, \theta) > l_i(w, \theta)$, for any w.*[23]

Proof: See Appendix 2.

This type of strategic behaviour has been neglected in the literature so far. Plugging $\bar{l}_i(w, \theta)$ into (16) yields the secondary market equilibrium allocation as a function of w:[24]

$$\bar{x}_i(w), \bar{a}_{ei}(w, \theta), \overline{em}_i(w) = \bar{x}_i(w) - \bar{a}_{ei}(w, \theta) = \bar{l}_i(w, \theta) \tag{19}$$

Similarly to Section 4.1 the primary market equilibrium is characterised by the permit price $\bar{w}(L, \theta)$, which balances the inelastic permit supply and the total permit demand, i.e. $L = \bar{l}_1(w, \theta) + \bar{l}_2(w, \theta)$. For given L, the strategic overinvestment in permits necessarily entails a higher equilibrium permit price compared to the case without commitment, i.e. $\bar{w}(L, \theta) > w(L, \theta)$. (19) combined with $\bar{w}(L, \theta)$ gives the Cournot Nash equilibrium allocation as function of the permit supply

$$\bar{x}_i(L, \theta), \bar{a}_{ei}(L, \theta), \overline{em}_i(L) = \bar{l}_i(L) \tag{20}$$

In the first stage of the game, the regulator chooses L in order to minimise total costs (10), anticipating the firms' response given by (20). The resulting optimal permit supply perfectly coincides with the one in Section 4.1, i.e.

$$\bar{L}^* = L^* = 2s^* \tag{21}$$

This is standing to reason, since, just like in the case without commitment, the regulator is capable of exactly controlling the total emission level, against what she cannot influence the latter's allocation between the firms. Thus, the respective minimisation problems are equivalent. Clearly, due to the inelastic permit supply, the firms' overinvestment is fully absorbed by the increase in w. Admittedly, this diminishes the firms' profits but is not detrimental for social welfare.[25] Finally, the comparative advantage of permits over standards and taxes, respectively, is given by

[23] In what follows, the bar denotes variables and functions that are specific to the case of strategic overinvestment.

[24] The explicit depiction is omitted since it yields tedious expressions but no further insights.

[25] In case the permits are grandfathered in the primary market, the side payments between firms associated with permit trade neutralize each other for which reason the increased price is without any consequences for social welfare, In case the permits are auctioned, a welfare-neutral application of revenues is taken for granted.

$$\Delta(\bar{L}^*, s^*) = E[TC(\boldsymbol{x}(s^*,\theta), \boldsymbol{a_e}(s^*,\theta),\theta) - TC(\boldsymbol{x}(\bar{L}^*,\theta), \boldsymbol{a_e}(\bar{L}^*,\theta),\theta)]$$
$$= \Delta AC(s^*, \bar{L}^*),$$

$$\Delta(\bar{L}^*, t^*) = E[TC(\boldsymbol{x}(t^*), \boldsymbol{a_e}(t^*,\theta),\theta) - TC(\boldsymbol{x}(\bar{L}^*,\theta), \boldsymbol{a_e}(\bar{L}^*,\theta),\theta)]$$
$$= 2Var[\theta]\left(\frac{d-\alpha}{z^2}\right) + \Delta AC(t^*, \bar{L}^*),$$

where $\Delta AC(s^*, \bar{L}^*) > \Delta AC(t^*, \bar{L}^*) > 0$.[26] (22)

From this follows
Proposition 3 *The optimal choice between tradable emission permits, emission standards and taxes for regulating a polluting Cournot duopoly with price taking behaviour in the permit market and strategic permit overinvestment obeys the following policy rule:*
(i) Permits should be preferred to standards in any case since $\Delta(\bar{L}^*, s^*) = \Delta AC(s^*, \bar{L}^*) > 0$.
(ii) Permits should be preferred to taxes if and only if $\Delta(\bar{L}^*, t^*) > 0 \Leftrightarrow 2Var[\theta]\left(\frac{d-\alpha}{z^2}\right) > -\Delta AC(t^*, \bar{L}^*)$.
The optimal choice between standards and taxes follows Proposition 1.

5.2 Examining the instruments' comparative advantage

As can be seen immediately from (22) and (13), the strategic overinvestment in permits does not impinge on the uncertainty related trade-off between permits, standards and taxes, respectively. This is standing to reason, since the additional permit demand is absorbed by the permit price and thus has no impact on the permit instrument's capability of exactly enforcing any aggregate emission level and thus guaranteeing a deterministic damage cost level. However, things are different in terms of abatement efficiency. The starting point here is the instruments' different performance in efficiently allocating the total abatement burden between firms, which has been revealed in Section 4.2. Contrary to permit trading without commitment, permits are no longer equivalent, but rather superior to taxes in this respect and similarly become even more preferable compared to standards. This is reflected by the fact that the optimal tax now causes a higher aggregate abatement cost level than permits ($\Delta AC(t^*, \bar{L}^*) > 0$) and the abatement cost difference between standards and permits increases in case of strategic overinvestment ($\Delta AC(s^*, \bar{L}^*) > \Delta AC(s^*, L^*)$). Apparently, market power on the output market, when combined with scope for commitment in terms of permit trading, actually benefits the tradable permits' comparative advantage. But for what reason? Clearly, the firm with relatively lower production costs ($i = 1$) similarly faces relatively higher costs of abatement via output reduction. Consequently, $i = 1$ has a higher incentive to overinvest in permits compared to $i = 2$ for a given permit endowment, as can be seen from (18):

$$\frac{\partial \pi_1(\cdot)}{\partial x_2(l_1,l_2,\theta)}\frac{\partial x_2(l_1,l_2,\theta)}{\partial l_1} - \frac{\partial \pi_2(\cdot)}{\partial x_1(l_1,l_2,\theta)}\frac{\partial x_1(l_1,l_2,\theta)}{\partial l_2} = \frac{b^2 z(V_2-V_1)}{(b+z+v)^2(3b+z+v)} > 0 \quad (23)$$

Thus, the emission rights are reallocated from $i = 2$ to $i = 2$ compared to the non-commitment case and tax-regime, respectively, i.e.

[26] The calculation of the abatement cost differences $\Delta AC(s^*, \bar{L}^*)$ and $\Delta AC(t^*, \bar{L}^*)$ is carried out perfectly analogous to Section 4.1. However, the explicit depiction of the results is omitted since it yields tedious expressions but no further insights. This similarly applies to all subsequent sections.

$$\left(l_1(\bar{L}^*) - l_2(\bar{L}^*)\right) - \left(l_1(L^*) - l_2(L^*)\right) = \left(l_1(\bar{L}^*) - l_2(\bar{L}^*)\right) - \left(em_1(t^*,\theta) - em_2(t^*,\theta)\right) = \left(\frac{b^2(V_2-V_1)(b+z+v)}{(b+v)\left(3b^3+v(z+v)(z+5v)+b^2(3z+7v)\right)}\right) > 0 \quad (24)$$

To sum up, state

Corollary 1 *The strategic overinvestment in emission permits depicted in Proposition 2 boosts the permit instruments' comparative advantage in terms of abatement efficiency, i.e.* $\Delta AC(s^*, \bar{L}^*) > \Delta AC(s^*, L^*)$ *and* $\Delta AC(t^*, \bar{L}^*) > 0$.

This is straightforward to see, since (24) entails a reallocation of market shares in favour of the more efficient firm, see (6) and (16), which decreases the gap between societal marginal abatement costs related to a decrease in x_1 and x_2, respectively, given in case without commitment and in the tax regime, see (15), and therefore decreases aggregate abatement costs as well. Thus, the optimal permit policy entails a lower aggregate abatement cost level than the optimal tax policy ($\Delta AC(t^*, \bar{L}^*) > 0$) and the difference in abatement costs between standards and permits growths ($\Delta AC(s^*, \bar{L}^*) > \Delta AC(s^*, L^*)$).

In total, standards still should be ruled, provided that the permit instrument is available. Care has to be taken since now the optimal choice between permits and taxes does not only depend on the uncertainty related trade-off, but rather, the respective abatement cost difference has to be considered as well.

6 Collusive behaviour

This section deals with the constellation in which market power additionally affects the permit market. More precisely, a thin permit market is assumed, i.e. the Cournot duopolists are the only firms to engage in permit trading and thus constitute a bilateral monopoly in the secondary market. As stated in Section 2.1, this allows firms for using the permit trade in order to coordinate their behaviour on the output market beyond the scope of antitrust authorities – provided that the permit endowment entails a credible commitment with respect to the emission and production capacity, like in the previous section.

6.1 Optimal instrument choice

Obviously, the firms' profit maximisation problem in the output market perfectly corresponds to the one described in Section 5.1, for which reason the related Cournot Nash equilibrium allocation is in turn given by (16). Since the secondary market comprises a bilateral monopoly, the adequate equilibrium concept is given by the Nash bargaining solution:[27] firms trade permits such that their joint profit in the output market is maximised, subject to the constraint that that the total amount of permits after trade is identical with the aggregate permit endowment transferred to the firms in the primary market:[28]

$$\max_{\{l_1,l_2\}} \pi_1(l_1,l_2,\theta) + \pi_2(l_1,l_2,\theta) \;\; s.t.\, l_1 + l_2 = q_1 + q_2 \quad (25)$$

[27] The alternative supply function approach is ruled out for the reasons stated above (see Section 2.2).

[28] Strictly speaking, the Nash bargaining solution involves maximising the Nash product. However, this is perfectly equivalent to the simpler problem given by (25), see for instance Requate (1993).

Note that the associated collusion in the output market cannot be tackled by antitrust authorities since (25) does not comprise direct agreements on the output level (c.f. Fehr 1993; Requate 1993; Fershtman and Zeeuw 1995). The associated first order condition states that the joint profit cannot be increased any more through a marginal reallocation of permits, i.e.

$$\frac{\partial\pi_1(l_1,l_2,\theta)}{\partial l_1}+\frac{\partial\pi_1(l_1,l_2,\theta)}{\partial l_2}+\frac{\partial\pi_2(l_1,l_2,\theta)}{\partial l_1}+\frac{\partial\pi_2(l_1,l_2,\theta)}{\partial l_2}=0 \tag{26}$$

The equilibrium trade results in the following permit allocation, which depends on the total initial permit endowment q_1+q_2, but not on its allocation between firms:[29]

$$\bar{\bar{l}}_i(q_1,q_2)=\frac{(V_{-i}-V_i)(2b+z+v)}{2\left(b^2+2bv+v(z+v)\right)}+\frac{q_1+q_2}{2} \tag{27}$$

The calculation of both the primary market equilibrium and the optimal permit supply is carried out perfectly analogous to Section 5.1, thus resulting in

$$\bar{\bar{L}}^*=\bar{L}^*=L^*=2s^* \tag{28}$$

Again, (28) is due to the fact that all the regulator can determine through the total permit supply is the total amount of emissions, but not its allocation between firms (see Section 5.1). Finally, the comparative advantage of permits over standards and taxes, respectively, is given by

$$\begin{aligned}\Delta\left(\bar{\bar{L}}^*,s^*\right)&=E\left[TC(\boldsymbol{x}(s^*,\theta),\boldsymbol{a_e}(s^*,\theta),\theta)-TC\left(\boldsymbol{x}\left(\bar{\bar{L}}^*,\theta\right),\boldsymbol{a_e}\left(\bar{\bar{L}}^*,\theta\right),\theta\right)\right]\\&=\Delta AC\left(s^*,\bar{\bar{L}}^*\right),\end{aligned}$$

$$\begin{aligned}\Delta\left(\bar{\bar{L}}^*,t^*\right)&=E\left[TC(\boldsymbol{x}(t^*),\boldsymbol{a_e}(t^*,\theta),\theta)-TC\left(\boldsymbol{x}\left(\bar{\bar{L}}^*,\theta\right),\boldsymbol{a_e}\left(\bar{\bar{L}}^*,\theta\right),\theta\right)\right]\\&=2Var[\theta]\left(\frac{d-\alpha}{z^2}\right)+\Delta AC\left(t^*,\bar{\bar{L}}^*\right),\end{aligned}$$

where, $\Delta AC\left(s^*,\bar{\bar{L}}^*\right)>\Delta AC\left(s^*,\bar{L}^*\right)>\Delta AC(s^*,L^*)>0$;

$$\Delta AC\left(s^*,\bar{\bar{L}}^*\right)>\Delta AC\left(t^*,\bar{\bar{L}}^*\right)>\Delta AC\left(t^*,\bar{L}^*\right)>0. \tag{29}$$

From this follows

Proposition 4 *The optimal choice between tradable emission permits, emission standards and taxes for regulating a polluting Cournot duopoly with collusive behaviour obeys the following policy rule:*

(i) Permits should be preferred to standards in any case since $\Delta\left(\bar{\bar{L}}^*,s^*\right)=\Delta AC\left(s^*,\bar{\bar{L}}^*\right)>0$.

(ii) Permits should be preferred to taxes if and only if $\Delta\left(\bar{\bar{L}}^*,t^*\right)>0\Leftrightarrow 2Var[\theta]\left(\frac{d-\alpha}{z^2}\right)>-\Delta AC\left(t^*,\bar{\bar{L}}^*\right)$.

The optimal choice between standards and taxes follows Proposition 1.

[29] In what follows, the double bar denotes variables and functions that are specific to the case of collusive behaviour.

6.2 Examining the instruments' comparative advantage

Still, the strategic – in this case collusive – behaviour of firms does not impinge on the instruments' trade-off with respect to uncertainty for familiar reasons. However, the opposite is true for abatement efficiency. With analogous reasoning to Section 5.1, it can be stated that strategic behaviour associated with market power boosts the permits' comparative advantage in minimising aggregate abatement costs, i.e., permits become preferable to taxes, i.e. $\Delta AC(t^*, \bar{\bar{L}}^*) > 0$, and even more preferable to standards, i.e. $\Delta AC(s^*, \bar{\bar{L}}^*) > \Delta AC(s^*, L^*)$, just like in case of strategic overinvestment. However, comparing the respective abatement cost differences yields additional insights which can be summed up by

Corollary 2 *The permits' comparative advantage over both standards and taxes in terms of abatement efficiency is boosted when market power does not only affect the output but also the permit market and firms thus trade permits to maximise joint profits; i.e. the related abatement cost differences increase compared to the case in which market power is restricted to the output market and firms engage in strategic overinvestment:* $\Delta AC(s^*, \bar{\bar{L}}^*) > \Delta AC(s^*, \bar{L}^*)$; $\Delta AC(t^*, \bar{\bar{L}}^*) > \Delta AC(t^*, \bar{L}^*)$.

The cause for this result can be revealed by opposing the first order conditions for permit trading in case of strategic overinvestment and collusive behaviour, (18) and (26). Since firms maximise joint profits in the latter case, they do not only take into account the impact of a marginal change in their permit endowment on own profit, but additionally consider the impact on the rival's profit, which is represented by $\partial\pi_i(l_1, l_2, \theta)/\partial l_{-i}$. Consequently, firms make use of $i = 1$'s comparative advantage in production costs and thus reallocate permits, and similarly market share, from $i = 1$ to $i = 2$:

$$\left(l_1(\bar{\bar{L}}^*) - l_2(\bar{\bar{L}}^*)\right) - \left(l_1(\bar{L}^*) - l_2(\bar{L}^*)\right) = \frac{b(V_2 - V_1)(b+v+z)^2(2b+v+z)}{((b+v)^2+vz)(3b^3+v(v+z)^2+b(v+z)(5v+z)+b^2(7v+3z))} > 0 \qquad (30)$$

This necessarily results in diminishing aggregate abatement costs as can be seen from (15) – abatement (through output shortage) is more costly for society when rendered by $i = 1$ – and, consequently, explains the increased abatement cost difference between permits, standards and taxes, respectively, depicted in (29), which immediately follows from (30) and (24).

7 Conclusion

This paper extends the theoretical literature on the optimal choice of pollution control instruments. In this respect, three main contributions are made. First, the paper provides for the first time a full comparative analysis of the three most common pollution control instruments – emission standards, tradable emission permits and emission taxes – which takes into account two features that are frequently given in actual regulation settings, namely market power of polluting firms and uncertain abatement costs from the regulator's perspective. Second, the paper reveals a new form of strategic permit trading that may arise even though the permit market is perfectly competitive. Finally, the rather pessimistic view concerning the impact of market power on the comparative advantage of tradable emission permits, which dominates in the literature so far, is qualified.

The starting point for the analysis is given by Heuson (2010), who reveals that Weitzman's (1974) famous policy rule for choosing price- versus quantity-based pollution control instruments is biased in case of market power by considering the case of a polluting Cournot oligopoly. However, Heuson (2010) neglects the instrument of tradable emission permits, since this, when combined with market power, gives rise to strategic behaviour that requires some separate effort in investigation. In this respect, this paper starts out with the benchmark case, assuming that the Cournot players face perfect competition in the permit market, whereas one (type of) player is more efficient in producing. Here, the price- and quantity-based instruments' trade-off in handling the regulator's uncertainty follows the adjusted policy rule derived by Heuson (2010). In terms of abatement efficiency, permits and taxes are equivalent and superior to standards in each case. Obviously, for the final instrument choice both the uncertainty-related trade-off and abatement cost difference have to be taken into account.

In a further step, the paper compares two contrary constellations in terms of market power that entail different types of strategic behaviour. The first constellation builds upon the benchmark case. Provided that the permit endowment entails a certain commitment effect with respect to the behaviour in the output market, firms engage in strategic permit overinvestment in order to gain market share from their rival. This possibility has been neglected in the literature so far. Provided that market power additionally affects the permit market, firms engage in collusive behaviour, i.e. they trade permits according to the Nash bargaining solution in order to maximise joint profits. In each case, the strategic behaviour leaves the uncertainty related trade-off between standards, permits and taxes unaffected. However, things are different concerning abatement efficiency. Both types of strategic behaviour boost the permits comparative advantage in this respect, i.e., permits cause lower abatement costs than taxes, while the abatement cost difference between standards and permits growths. In other words, market power improves the permits' performance in this sense. This is for the reason that both types of strategic behaviour cause a shift of permits and hence market share to the firm with lower production costs and, thus, higher costs of abatement via output shortage. Consequently, aggregate abatement costs decrease compared to the other instruments and the case without strategic behaviour, respectively. In case of strategic overinvestment, the shift is due to the fact, that the firm with lower production costs has a stronger incentive to invest in permits for increasing its profit. On contrary, when market power affects both markets, firms maximise joint profits. For this reason, the impact of a firm's permit endowment on the rival's profit is internalised. Obviously, this provides additional incentives to shift permits to the more efficient firm, thus enabling that the latter contributes more to the total output level. To sum up, the boost in the permits' comparative advantage is even stronger when both the output and permit market are subject to market power.

Clearly, these findings put the rather pessimistic view on market power and the performance of tradable emission permits somewhat into context. However, care has to be taken as the results are tied to the assumption of an interior solution which is taken for granted in Heuson (2010) and Weitzman (1974), respectively. According to this assumption, both firms render a positive output and end-of-pipe abatement level in the subgame perfect equilibrium, which in turn requires the optimal emission level to be sufficiently (but not too) low (see Section 3). In cases where this condition is not fulfilled, firms may abstain from end-of-pipe abatement and advance the permit shift towards the more efficient firm in order to achieve monopolistic profits (c.f. Fehr 1993; Fershtman and Zeeuw 1995). From the welfare perspective, this constellation is ambiguous, since the associated gain in abatement efficiency has to be traded off against the deadweight loss due to monopolisation and the related output shortage. However, a detailed judgement requires some separate effort in investigation which goes beyond the scope of this paper. This is for the reason that monopolisation involves a corner solution, which is no longer consistent with the underlying framework of Heuson (2010) and Weitzman (1974), respectively.

Appendix 1 Output reaction functions (Section 5.1)

The output reaction function of firm i, $rx_i(x_{-i}, l_i, \theta)$ directly follows from the solution of the firm's profit maximization problem in the output market, i.e. from (1), whereas s is replaced through l_i:

$$rx_i(x_{-i}, l_i, \theta) = \frac{B-V_i-Z-\theta+zl_i}{2b+z+v} - \frac{b}{2b+z+v}x_{-i} \tag{A1.1}$$

Obviously, the firms' output levels are strategic substitutes, i.e. the reaction function's slope is negative

$$\frac{\partial rx_i(x_{-i},l_i,\theta)}{\partial x_{-i}} = -\frac{b}{2b+z+v} < 0 \tag{A1.2}$$

Furthermore, i's permit endowment, l_i, leaves the reaction function's slope unaffected, i.e.,

$$\frac{\partial rx_i(x_{-i},l_i,\theta)}{\partial x_{-i}\partial l_i} = 0, \tag{A1.3}$$

but influences its level with positive sign

$$\frac{\partial rx_i(x_{-i},l_i,\theta)}{\partial l_i} = \frac{z}{2b+z+v} > 0. \tag{A1.4}$$

From this immediately follows that an increase in the permit endowment leads to a parallel outwards shift of the respective firm's reaction function, as illustrated in Figure 1.

Appendix 2 Proof of Proposition 2

$\bar{l}_i(w,\theta)$ immediately follows from solving the system given by (18). Then we have

$$\frac{\partial(\bar{l}_i(w,\theta)-l_i(w,\theta))}{\partial B} = \frac{b^2+3b+z+v}{(3b+v)(9b^3+v(z+v)(3z+7v)+b^2(11z+15v))} > 0 \tag{A2.1}$$

The existence of the interior solution defined in Section 3 requires among others

$$x_i(w) > 0 \Rightarrow B > w + V_i + \frac{b(V_i-V_{-i})}{2(b+v)} \tag{A2.2}$$

From this follows

$$\bar{l}_i(w,\theta) - l_i(w,\theta)\Big|_{B=w+V_i+\frac{b(V_i-V_{-i})}{2(b+v)}} = 0 \tag{A2.3}$$

Considering both (A2.1) and (A2.3) proves that $\bar{l}_i(w,\theta) - l_i(w,\theta)$ is strictly positive for any w.

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