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September 2010

**Centre for Climate Change Economics and Policy
Working Paper No. 34**

**Grantham Research Institute on Climate Change and
the Environment**

Working Paper No. 25

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Environmental Economics and Modeling Marketable Permits*

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February 2009

Abstract

This paper reviews fundamental concepts in environmental economics and explores theoretical results regarding the choice of the key policy instruments for the control of externalities: taxes, subsidies and marketable permits. The paper explains why today market mechanisms are increasingly being used as a tool for allocating unpriced rights and scarce resources. We survey how significant market imperfections, a pre-existing regulatory environment and concentration in both permit and output markets can impede the proper functioning of a permit system. The main factors that affect the effectiveness of marketable permits are then discussed. Given the importance of understanding the emission permit price formation, we overview recent attempts at developing valid price models for emission permits, taking into account banking and borrowing opportunities, pollution abatement measures, strategic trading interactions and the presence of asymmetric information in the permit market.

Keywords: Dynamic Price Modeling, Emission Permits, Market Imperfections.

JEL Classifications: Q50, Q58, Q56, C60, G13.

*Part of the author's research was supported by the University Research Priority Program "Finance and Financial Markets" and by the National Centre of Competence in Research "Financial Valuation and Risk Management" (NCCR FINRISK), research instruments, respectively, of the University of Zürich and of the Swiss National Science Foundation.

The author would like to thank Federica Buricco, Takanobu Kosugi and the participants of the "8th Ritsumeikan International Symposium on Stochastic Processes and Application to Mathematical Finance - 8th Columbia Jafee Conference" (Kyoto - Japan) for their helpful discussions and comments. The financial support of the Heiwa Nakajima Foundation to the Special Session on Environmental Finance is gratefully acknowledged.

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1 Introduction

Global warming is at the top of many agendas, particularly nowadays where virtually every aspect of economic activity results in greenhouse gas emissions (GHG), whose concentration promotes global warming. In the last decade several organizations and policy regulators have been studying and discussing with (environmental) economists possible strategies to tackle this problem. Economists had what they saw as a coherent and compelling view of the nature of pollution, with a straightforward set of policy implications. In fact, the problem of externalities¹ and the associated market failure had long been a part of the microeconomic theory. Economists saw pollution as the consequence of an absence of prices for certain scarce environmental resources such as clean air and water, and they prescribed the introduction of surrogate prices in the form of unit taxes or “effluent fees” to provide the needed signal to economize on the use of these resources. This explains why the source of the basic economic principles of environmental policy is to be found in the theory of externalities. The literature on this subject is enormous: it encompasses hundreds of books and papers. An attempt to provide a comprehensive and detailed description of the literature on externalities theory reaches beyond the scope of this survey. Instead, we shall try in this paper to outline the central results from this literature, with an emphasis on their implication for a quantitative analysis of the price formation of the most popular policy measure today: marketable permits. The aim of the paper is to provide a basic knowledge about the theoretical results behind marketable permits as policy instruments and to facilitate the development of more sophisticated quantitative models which try to describe those markets for permits existing today.

We begin in section ?? with a review of the theory of environmental regulations and we explore theoretical results regarding the choice of key policy instruments for the control of externalities: taxes, subsidies and marketable permits. Section ?? overviews those factors, addressed by several authors in the last two decades, that affect the effectiveness of marketable permits. Section ?? analyzes the recent attempts to develop valid static and dynamic price models for marketable permits employed in air-pollution controls. Section ?? concludes.

2 Main Concepts in Environmental Economics

Taxes, subsidies and marketable permits In a competitive market, firms with free access to environmental resources will continue to engage in polluting activities until the marginal return of their production is zero. We thus obtain the familiar result that, because of their disregard for the external costs that they impose on others, polluting agents will engage in socially excessive levels of polluting activities. The policy implication of this result is then clear in economics. Polluting

¹Externalities refers to situations where production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided.

agents need to be confronted with a price equal to the marginal external cost of their polluting activities to induce them to internalize at the margin the full social costs of their pursuits. Such a price incentive can take the form of the familiar “Pigouvian tax” - named after ?. This is a levy on the polluting agent equal to the marginal social damage. Figure ?? illustrates how a Pigouvian tax works. The imposition of a unit tax on pollution emissions produces an upward shift of the marginal cost curve by the amount of the tax, i.e. from MC_I to MC_{II} . Faced with this cost increase, each company has an incentive to reduce output from q_n to q_t , i.e. to the socially optimal level.

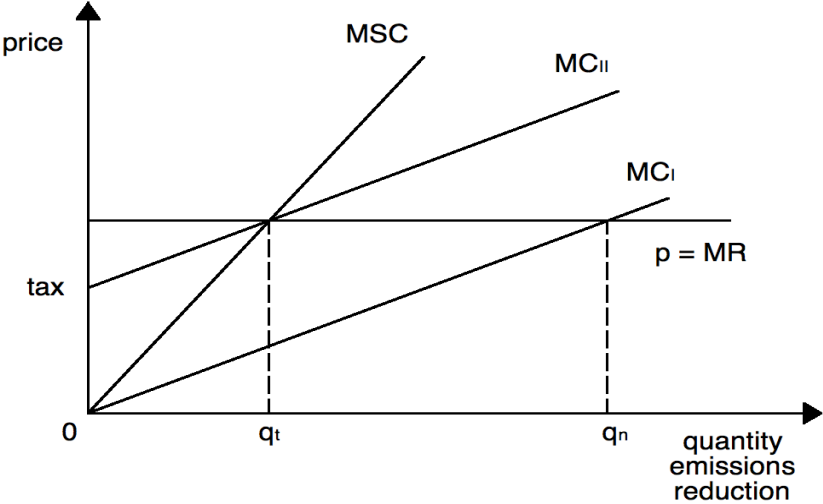


Figure 1: The Pigouvian tax as a price system. MSC stands for marginal social cost, MC for marginal cost and MR for marginal return.

Besides a tax on polluting activities, two alternative policy instruments have received extensive attention in the literature: subsidies and marketable permits. Early on it was recognized that a subsidy per unit of emission reduction could establish the same incentive for abatement activity as a tax of the same magnitude per unit of pollution emitted. Soon it became apparent that there are important asymmetries between these two policy instruments - see ? for a comprehensive analysis. In particular, these two policy instruments have quite different implications for production profitability in a polluting industry: subsidies increase profits, while taxes decrease them. It may be helpful to explain this argument with an illustration. In figure ?? we depict the equilibrium positions of a representative company and its corresponding industry in three different situations: no environmental regulations; unit tax on pollution emissions; and unit subsidy for emission reductions. Starting from the equilibrium point (q_n, p_n) where there are no-environmental regulations, we observe that a unit tax produces an upward shift in the company’s marginal and average cost curves to $MC_{t,s}$ and AC_t respectively. If, instead of having

no-environmental regulations, we consider a program of subsidies, the company's marginal cost shifts up to $MC_{t,s}$, but its average cost is now reduced to AC_s - see ?.

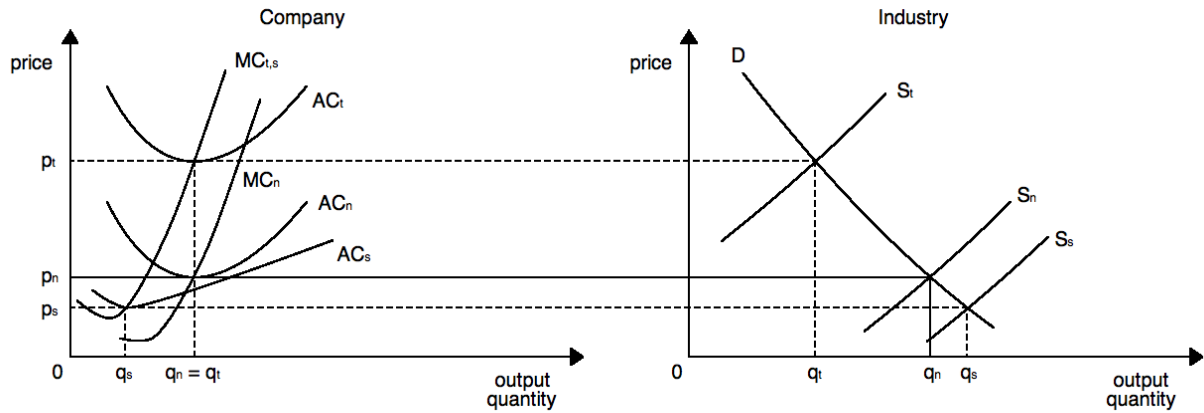


Figure 2: Tax and subsidy. MC and AC stand for marginal cost and average cost curves, respectively. D is the aggregated demand curve of the output product, and S is the industrial supply curve.

We notice then that tax and subsidy programs have identical effects on a company's marginal costs. However, considering the pollution emissions of a whole industry, we note that the Pigouvian tax must result in a leftward shift of the industrial supply curve, from S_n to S_t , because tax raises company's marginal and average costs. Further, output price rises from p_n to p_t and industry output falls from q_n to q_t with a consequent decline in the industry's pollution emissions. Conversely, the subsidy induces the entry of new companies producing the rightward shift of the industry supply curve from S_n to S_s . This result in a price fall to p_s and an increase in the industry's output to q_s and consequently in its pollution emissions. These two policy instruments, therefore, have quite different implications for firms' long-run, entry-exit decisions. This implies that there is a further condition, an entry-exit condition, that long-run equilibrium must satisfy in order to achieve an efficient outcome when designing a subsidy program. To obtain the correct number of firms in the long run, it is essential that the firms pay not only the cost of the marginal damages of their emissions, but also the total cost arising from them. Only if firms bear the total cost of their emissions, will the prospective profitability of the enterprise reflect the true social net benefit of entry and exit into the industry. However, a detailed discussion about tax and subsidy programs is beyond the scope of this paper, and we refer interested readers to the literature we cite in the body of the text.

The Pigouvian solution to the problem of externalities has been the subject of repeated attack along Coasian lines. ? has elaborated on the externalities question by emphasizing that the root

of the problem is that of undefined property rights. He claims that if the ownership rights to clean air, for instance, were clearly defined and enforced, then self-interested parties would use legal and market mechanisms to bring about a socially acceptable level of externalities. However, such a theory holds only in the absence of transaction costs and strategic behaviour (more on this in the next section). Following Coase's principle, environmental economists introduced market-based instruments so-called marketable permits. Suggested applications for the use of market approach abound in the economics literature, especially in the fields of air and water pollution - see ?. In a world of perfect knowledge, marketable emission permits are a fully equivalent alternative to unit taxes. The environmental authority can set a price (i.e. a tax) and then adjust it until emissions are sufficiently reduced to achieve a prescribed environmental standard. Alternatively, it can issue the requisite number of permits directly and allow the bidding of polluters to determine the market-clearing price. The regulator can, in short, set either "price" (tax) or "quantity" (emission cap) and achieve the desired result. However, the basic equivalence obscures some crucial practical differences between the two approaches in a policy setting; they are by no means equivalent policy instruments from the prospective of a regulatory agency. A major advantage of the marketable permit approach is that it gives the environmental authority direct control over the quantity of emissions. Under the tax approach, the regulator must set a tax, and if, for example, the tax turns out to be too low, the pollution will exceed permissible levels. In sum, the regulatory agency might have to enact periodic (and unpopular) increases in taxes. In contrast, a system of marketable permits automatically accommodates itself to growth and inflation. Since there can be no change in the aggregate quantity of emissions without some explicit action on the part of the agency, increased demand will simply translate itself into a higher market-clearing price for permits, with no effects on levels of pollution. On the other hand, polluters are likely to prefer the permit approach because it can involve lower levels of compliance costs. Besides practical differences, the symmetry between price and quantity approaches is critically dependent upon the assumption of perfect knowledge. In a setting of imperfect information concerning cost functions and the marginal benefit that can potentially be achieved, the outcomes under the two approaches can differ in important ways, as described in the next paragraph.

Price vs. Quantity In a seminal paper, ? investigated the asymmetry between price and quantity instruments and produced a theorem with extremely important policy implications. The theorem establishes the conditions under which the expected welfare gain under a unit tax either exceeds, is equal to, or falls short of that under a system of marketable permits (quotas). In short, the theorem states that in the presence of uncertainty concerning the costs of pollution control, the preferred policy instrument depends on the relative steepness of the marginal benefit and cost curves. Weitzman's intuition is straightforward. Consider, for example, the case where the marginal benefits curve is quite steep but marginal control costs are fairly constant over the

relevant range. This could reflect some kind of environmental threshold effect where, if pollutant concentrations rise only slightly over some range, dire environmental consequences follow. In such a setting, it is clearly important that the environmental authority has a close control over the quantity of emissions. If, instead, a price instrument were employed and the authority were to underestimate the true costs of pollution control, emissions might exceed the critical range with a resulting environmental disaster. In such a case, the Weitzman theorem tells us that the regulator should choose the quantity instrument because the marginal benefits curve has a steeper absolute slope than the marginal cost curve. Suppose, next, that it is the marginal abatement cost curve that is steep and that the marginal benefits from pollution control are relatively constant over time. The danger here is that because of imperfect information, the regulatory agency might, for example, select an overly stringent standard, thereby imposing excessive costs on polluters and society. Under these circumstances, the expected welfare gain is larger under the price instrument. Polluters will not get stuck with inordinately high control costs, since they always have the option of paying the unit tax on emissions rather than reducing their pollution further. It may be helpful to explain this argument with an illustration. In figure ?? we depict two marginal benefit curves MB ranging from horizontal MB_I to vertical MB_{II} . E is the point where the expected marginal cost curve MC_E crosses the marginal benefit curves. Based on the expected marginal cost curve, the regulator will select a tax level \mathcal{T} under a price system, or, alternatively, a number of permits q_p under a quantity system. If MC_R turns out to be the actual marginal cost curve, the price approach will result in emission reduction of q_t . In the situation of a horizontal marginal benefit curve MB_I , the price instrument achieves the true optimal outcome q_t . The quantity instrument, instead, produces a distortion equal to $(q_p - q_t)$. The opposite is true in the other extreme case MB_{II} : the permit approach produces the optimal outcome and the tax approach results in a distortion equal to $(q_t - q_p)$. An identical argument shows in a similar fashion that this relationship holds when the realized marginal cost curve MC_R lies above the expected marginal cost curve.

The Weitzman theorem thus suggests the conditions under which each of these two policy instruments is to be preferred to the other in the presence of abatement cost uncertainty. Not surprisingly, an expected outcome even more favourable can be obtained by using price and quantity instruments in tandem, see ?. After two decades, ? showed that benefit uncertainty also matters. In particular, the instrument-neutrality long identified with equal absolute valued slopes of marginal benefits and marginal costs likewise disappears when there exists a significant correlation between them. Quite remarkably, Stavins' results suggest that the conventional identification - under Weitzman policy instrument recommendations - of a price (tax) instrument can in fact be reversed, to favor instead a quantity (marketable permits) measure. On the other hand, his results also suggest that it is less likely that the conventional identification of a quantity measure as being more efficient to a price measure will be reversed.

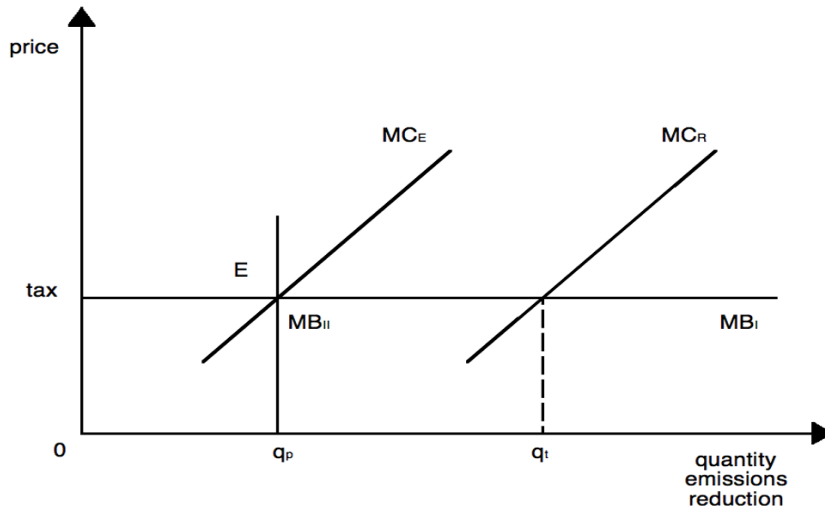


Figure 3: Price system versus quantity system. MB stands for marginal benefit curve, and MC for marginal cost.

Emission Trading Programs Largely for the reasons mentioned above, policy makers in the U.S. have found marketable permits preferable to taxes and subsidies as a mechanism for providing economic incentives for pollution control. The major program of this genre is the Emission Trading Program for sulfur dioxide (SO_2) organized by the American Environmental Protection Agency. This market was created under the 1990 Amendments to the Clean Air Act. It was designed to address the acid rain problem by cutting back annual sulfur emissions by 10 million tons. This market in principle grants relevant power plants to meet their emission reduction quotas by whatever means they wished, including the purchase of extra emission reductions from other sources, i.e. other firms. The scheme significantly increased the flexibility with which sources can meet their pollution limitations. This has been important as it has allowed substantial cost savings - see ? for further detailed descriptions. In the early stages the great majority of the trades have been internal ones.² A real and active market in emissions permits involving different firms has recently begun to develop under the program.

Conversely, in the past, the use of taxes was more prevalent in Europe where they were extensively employed in systems of water quality management - see ? for a complete summary. However, taxes were typically low and have tended to apply to average or expected pollution rather than to provide a clear cost signal at the margin. Moreover, the charges were overlaid on an extensive command-and-control system³ of regulations that mute somewhat further their effects as economic incentives. Recently, following the example of the Kyoto protocol, European

²This fact explains the large presence of zeros in the return time series of SO_2 . For an in deep econometric analysis of the U.S. market for SO_2 see ?.

³These are typically programs under which the environmental authority prescribes the treatment procedures that are to be adopted by each source.

policy makers implemented the largest and most important market for emission permits: the European Emission Trading Scheme (EU ETS). At its launch in 2005, the scheme covered the carbon dioxide (CO₂) emissions from energy-intensive industry sectors in the then 25 member states, responsible for nearly half of the EU's CO₂ emissions. Today, the scheme includes 27 countries and claims 80 per cent of the value of the world's markets for marketable permits. The scheme has so far worked as it was envisioned: a European-wide price on emission of CO₂ was established, businesses began incorporating this price into their decision-making, and the market infrastructure for a multi-national trading program is now in place.

Since market-based instruments are extensively being used as a tool for pollution control at a regional and international scale, there is an increasing need to develop effective dynamic models for the price of marketable permits. In fact, a valid price model is an essential component for any decision-making process, and for constructing optimal hedging and purchasing strategies in a (GHG and carbon) constrained market. Furthermore, firms trade permits not exclusively for compliance purposes but some take also speculative positions, as ? claim in their working paper. Addressing the important aspect of effective models, the last section surveys the few model attempts which exist in literature.

3 Factors which Affect the Performances of Marketable Permits Systems

One of the first references to marketable permits can be found in the seminal works of ? and ?. In these papers pollution-abatement problems are viewed within an economic, cost-benefit framework in conjunction with the concept of property rights introduced in the previous section. Based on such an idea, ? provides a rigorous theoretical justification of how marketable emission permits lead to an efficient allocation of abatement costs across various "sources of pollution". Necessary and sufficient conditions for market equilibrium and efficiency are derived, given the setting of multiple profit-maximizing firms who attempt to minimize total compliance costs. Literature discussing those factors which can adversely affect the performance of marketable permit systems - and which are not addressed directly in Montgomery (1972) - has been abundant. Among the most important instances, concentration in the permit and output market have been exploited by ?, ?, and by ? respectively. The pre-existing regulatory environment has been discussed by ? and the degree of monitoring and enforcement by ?. ? has considered the presence of non-negligible transaction costs in the market. We briefly overview these and other papers below.

Marketable Permits and Market Manipulation The appeal of using marketable permits as a means of allocating scarce resources stems in large part from the assumption that a market

for permits will approximate to the competitive ideal. When the competition is not a foregone conclusion, the question arises as to how a firm might manipulate the market to its own advantage. ? has discussed such issues as market manipulation developing a one-period model where one firm has market power and all transactions of emission permits take place at a single price. The author's principal finding is that the degree of inefficiency observed in the market is systematically related to the distribution of permits. In other words, in the presence of market power, the initial distribution of permits matters - with regard not only to equity considerations but also to cost.⁴ That is to say, it is the demand of the firm with market power which determines the equilibrium price of emission permits. Building on the theory of cost-minimizing manipulation and the literature on raising rivals' costs, ? have discussed a different form of market manipulation: exclusionary manipulation. Because permit prices are sensitive to the purchases (or sales) of the firm with market power, exclusionary manipulation can aggravate the inefficiencies which occur in both the market for permits and the product market.⁵ Similarly, the efficiency of marketable permit systems depends on the competitiveness of the output markets in which polluting firms compete. ? has shown that the introduction of marketable permits increases aggregate "welfare" if output markets are competitive. In contrast, in the presence of non-competitive output markets, a system of emission permits may reduce social "welfare" even if the market for the emission permits is perfectly competitive.

Marketable Permits and Preexisting Regulatory Environments The strength and effectiveness of the incentives created by a cap-and-trade scheme will depend in large part on the rules that regulators apply to marketable permits schemes. These rules will determine how affected firms will be compensated for investments in emission permits and whether ratepayers and shareholders will share in the benefits of trading emission permits. The influence of uncertainty regarding the regulation policy of public utility commissions in the U.S. market for SO₂ have been discussed by ?. The authors develop and analyze a model of individual utility decisions that focuses on the choice between purchasing permits or investing in SO₂ abatement measures to comply with the law. Their key finding is that policy rules influence the relative cost of investments in emission permits versus switching to low sulfur fuels (a medium-term abatement measure) or investments in emission control equipment (typically long-term abatement measures). Furthermore, the authors show that such rules may distort the incentives for utilities to adopt the least-cost combination of emission permits and other compliance strategies required to satisfy U.S. regulations.

⁴Traditional models of marketable permits view problems of initial permit distribution as being strictly an equity issue. The analysis of ? provides an example where all firms are assumed to be price takers. For the case of one pollutant, the author finds that the distribution of permits will have no effect on achieving the target in a cost-effective manner.

⁵Anticipating the discussion in the next section, in ? the dynamics of the permit price results from the interactions of buyers and sellers orders in the permit market.

Marketable Permits and Enforcement Degrees The degree of monitoring and enforcement has also been the subject of several studies. ?, for instance, extends the previous research on marketable permits in the presence of noncompliant firms. The author makes a specific comparison between command-and-control and marketable permits systems when regulatory authorities are unable to achieve full compliance. In particular, Keeler studies the sensitivity of the shape of the penalty function faced by non-compliant firms. His analysis indicates that under plausible penalty functions, marketable permits may allow more pollution or higher fraction of regulated non-compliant firms. These results highlight that the success of pollution control strategies reliant on marketable permits deeply depends on implementation schemes.

Marketable Permits and Transaction Costs Since ?, the presence of transaction costs in the U.S. markets for SO₂ permits has been regarded as a fact. Though ? and ?, among several other authors, had already commented on the potential importance of transaction costs in the markets for emission permits, ? was the first who formally includes transaction costs into an analytic model. Another source of indirect evidence of the prevalence of transaction costs in the U.S. market for SO₂ permits comes from the well-documented “internal trading”, as opposed to “external trading” among firms.⁶ It has been hypothesized that the crucial difference favoring internal trades and discouraging external ones is the existence of significant transaction costs that arise when trades are between one firm and another -see ?. Stavins claims that transaction costs reduce the volume of permits trading, regardless of the specific form the marginal control-cost and transaction-cost functions take. This holds insured the marginal control cost functions are nondecreasing. A formal proof of this statement is found in ?. Not surprisingly, equilibrium permit allocations are sensitive to initial distributions of permits. This result is fully consistent with the Coase Theorem, ?, which states that in the presence of transaction costs, the anticipated outcome from a process of bilateral negotiation is variant with respect to the initial assignment of property rights. In sum, the presence of transaction costs reduce trading levels and lower the discretion of each environmental agency which, as opposed to ?, “can[not] distribute licenses as it pleases.”

The attempt to find a specific initial permit allocation to overcome some of the problems described so far, can actually result in a scheme that will be far more costly than planned. This may argue for the economist’s favorite permit-allocation mechanism: Auctions. This approach, for instance, becomes even more attractive in the presence of transaction costs. ? have analyzed the distributional implications of allocating CO₂ emission permits through auctions rather than through some form of *grandfathering*.⁷ The authors argue that auctioning is superior because

⁶Again, this fact justifies the large presence of zeros in the return time series of the SO₂, as mentioned in a previous footnote.

⁷For a detailed discussion of initial allocation criteria see ? and references therein. For a comprehensive analysis

it increases efficiency by reducing existing tax distortions; it also offers greater incentives for innovation and gives more flexibility in the distribution of costs; finally, it reduces the need for politically contentious arguments over the allocation of rents. On this latter issue, ? considers a construction of an allocation scheme in the presence of market power. Prior to this, ?? conducted an experimental analysis on auction and rules design. However, as also pointed out by some of the previous authors, auctions may not necessarily be chosen - and in fact are scantily employed - due to vested interests introducing a powerful voice in favor of grandfathering.

4 Modeling Marketable Permits

Literature which focuses on the mechanism-design and on economic and policy implications of marketable permits is extensive, as is clear from previous sections. However, an explicit and formal study of the price dynamics of emission permits is an almost-unexplored area. Most of the present research relies on Montgomery’s key findings: in a competitive market with perfect information, the equilibrium price of the emission permits is equal to the marginal costs of the cheapest pollution abatement measure. This statement underpins the belief that a high price level for emission permits brings about the relevant companies with lower marginal abatement costs in order to exploit consequent price differences. Such companies make profits by lowering the level of pollution more than is necessary, in order to comply with regulations and subsequently sell their unused permits and relying on banking opportunities.⁸

The Permit Market under Certainty Instead of limiting inter-temporal trading to banking, ? allows both borrowing and banking and extends the work of ? and ? providing a more general treatment of permit trading in continuous time by means of optimal-control theory. In particular, the author explores the problem of minimizing the inter-temporal cost ($C(e_t)$) of reducing pollution by modeling a general firm in the presence of emission permits that are tradable across firms and through time ($x_t, t \in [0, T]$). In such a setting, firm i -th ($i = 1, \dots, \mathcal{I}$) may directly abate emissions ($e_{i,t}$), and it may purchase ($x_{i,t} > 0$), sell ($x_{i,t} < 0$), bank ($B_{i,t} \geq 0$) or borrow ($B_{i,t} < 0$) emission permits in order to meet regulations or take advantage of any opportunity that may arise. Rubin evaluates individual firms that optimally control abatement costs and permit purchases and sales, given a risk-free rate of interest (r), an initial endowment

of the social and economic impact of allocation criteria see ? and ?.

⁸To generate permits, a firm may choose to pollute less than the current permitted level and sell the “unused” permits to a different firm or deposit them in an “emission bank account” to be used later by the firm or sold at a later time to another firm. The borrowing of permits occurs when a firm pollutes more than its current permitted level, but the cumulative deficit must be repaid by the end of the scheme.

of permits (N_i) and an exogenous permit price (S_t)

$$\begin{aligned} \min_{x_i, e_{i,t}} \int_0^T e^{-rt} [C_i(e_{i,t}) + S_t \cdot x_{i,t}] dt & \quad (1) \\ \text{s.t. } B_{i,t} = N_i - \int_0^t (e_{i,s} - x_{i,s}) ds; \quad B_{i,0} = 0; \quad e_{i,t} \geq 0. & \end{aligned}$$

Necessary conditions for optimization imply that each firm purchases or sells x_i permits until the discounted marginal cost of a permit in its bank account equals the discounted price of a permit. Solving the minimization problem, Rubin shows that each firm equates marginal costs of pollution abatement with the price of an emission permit, i.e. $-\partial C_i(e_{i,t})/\partial e_{i,t} = S_t$. In particular, the marginal cost is shown to be constant in time when each firm can bank and borrow permits. Conversely, if the firm desires to borrow but this is not permitted, the marginal cost decreases in time. A special case arises when the discount rate is nil. In this situation firms will have no incentive to undertake abatement measures until a future date. If pollution emission rates becomes more strict through time, firms tend to save more or buy more permits in the beginning for later use. Conversely, higher discount rates lower the value of future cost savings and decrease the incentive for firms to bank permits. One of the most important findings of this paper is the identification of the ability of firms to shift their emission stream through time as a consequence of banking and borrowing. In particular, when social damages are an increasing function of the level of pollution emitted at any one time and pollution standards become stricter through time, banking is a positive option. It provides cost saving to firms by allowing them to adjust their own internal rates of emission reduction to pollution standards set externally by regulations. However, when regulations impose constant or easing pollution standards, then allowing firms to borrow raises social damages while lowering the firms' costs. Though ? provides a comprehensive treatment of inter-temporal emission trading, its analysis has been framed in a world of certainty where the permit price is assumed to be exogenous.

? attempts to overcome the first limitation. The author takes explicitly into account the non-negativity constraint on banking, i.e. ($B_t \geq 0$). In fact, programs like Title IV do not allow emission permits to be borrowed from future allocations. Schennach explores the consequences of this constraint on the paths of the emission permits price and of the SO₂ emissions in the U.S. market.⁹ The author models all U.S. utilities (energy companies) as a single central planner who faces an infinite-horizon optimization problem. The aim of the paper is to solve the inter-temporal optimization problem faced by the central planner who is subject to electricity demand constraints (ϵ_t)¹⁰ and has to decide how much SO₂ to reduce (a_t), considering the future costs of

⁹Readers interested in the effects of banking opportunities on social welfare are referred to ? and references therein.

¹⁰ ϵ_t is the SO₂ emission that would be needed to satisfy the demand for electricity at time t without any SO₂

abatement ($C(a_t)$).

$$\begin{aligned} \min_{e_t} \int_0^\infty e^{-rt} C(a_t) dt \quad \text{where} \quad a_t = \epsilon_t - e_t \quad (2) \\ \text{s.t.} \quad B_t = N - \int_0^t e_s ds; \quad e_t \geq 0; \quad B_0 = 0; \quad B_t \geq 0. \end{aligned}$$

As in ? in the ideal world of certainty, discounted marginal abatement costs equal the marginal cost of an additional unit of banked emission. However, under borrowing constraints, Schennach shows that the evolution of the central planner's behavior over time can be divided into two periods. The first is the banking period where the price of the emission permits increases at the discounting rate ($S_t = e^{rt} \cdot C'(a_0)$). This is followed by a period where banking stops and the price of the emission permits follows changes in both the marginal cost of abatement and changes in electricity demand ($S_t = \partial C(a_t) / \partial a_t$). The determination of the path of permits price and pollution emissions is not analytically tractable unless a functional form for both marginal cost function and growth in electricity demand are postulated. Nevertheless, Schennach's findings make it possible for the first time to describe the impact of important factors, such as the availability of low-sulfur coal and the growth in demand for electricity, on the SO₂ permit market. Similarly to ?, Schennach recognizes the importance of banking options to smooth out the interjection of possible jumps in the marginal cost function of pollution abatement. Finally, and more appealingly, introducing uncertainty in the marginal cost of abatement ($C(a_t)$) and in the demand for electricity (ϵ_t), ? provides one of the first attempts to study the emission permit price in a stochastic, continuous-time and infinite-time horizon model. The optimization problem in the presence of uncertainty becomes

$$\begin{aligned} \min_{e_t} \mathbb{E}_0 \left[\int_0^\infty e^{-\rho t} C(\epsilon_t - e_t) dt \right] \quad (3) \\ \text{s.t.} \quad B_t = N - \int_0^t e_s ds; \quad e_t \geq 0; \quad B_0 = 0; \quad B_t \geq 0. \end{aligned}$$

where the discount rate ρ is constant and $\mathbb{E}_t[\cdot]$ stands for the conditional expectation $\mathbb{E}[\cdot | \mathcal{F}_t]$. Though Schennach does not provide an exact analytic solution for (??), she conjectures that the actual path of price and emissions may be quite different from their expected path. When new information becomes available, the optimization problem has to be re-evaluated, possibly generating cusp or discontinuity in the path of emissions and of price. This is precisely the approach developed in ?.

The Permit Market under Uncertainty The results of ? reveal that, when allowed to trade with one another, firms will collectively behave like a central planner who efficiently allocates emission permits to each firm to minimize total costs. This allows ? - and previously ? - to

abatement requirements.

simplify the analysis and model all firms as a representative agent who coincides with the central planner. In ? the representative agent decides whether or not to spend money on lowering emission levels. The model is based on the optimal abatement decision (u_t)¹¹ of the risk-neutral representative agent who has no opportunity, however, to trade permits. The agent continuously emits offending gas (Q_t) over the whole regulated period $[0, T]$ and its pollution dynamics evolve according to an arithmetic Brownian motion $dQ_t = \mu dt + \sigma dW_t$.

$$\min_{u_t} \mathbb{E}_0 \left[\int_0^T e^{-rt} C(t, u_t) dt + e^{-rT} S(T, \delta_T) \right] \quad (4)$$

where

$$C(t, u_t) = -1/2 \cdot c \cdot u_t^2$$

describes the abatement costs per unit of time;

$$S(T, Q_T) = \min(0, P \cdot (N - \delta_T))$$

describes the potential penalty (P) costs at the end of the trading period T ; and

$$\delta_T = - \int_0^T u_s ds + \mathbb{E}_t \left[\int_0^T Q_s dt \right]$$

is the difference between the pollution abatement and the total expected emissions over the period $[0, T]$, i.e. the net amount of emissions. By means of stochastic optimal control, the authors derive a partial differential equation which describes the spot price dynamics of the emission permits. The partial differential equation can be solved analytically only when $r = 0$ and the pollution dynamics follow a white noise process, i.e. $dQ_t = \sigma dW_t$. This is a very special and restricted case, and numerical techniques are required for more general pollution dynamics. Unfortunately, there is no clear interpretation of the analytic solution. Nevertheless, the authors study how significant factors affect the spot price of the emission permits. In particular, they show that the price rises with increasing penalty costs (P), expected pollution emissions (δ_t), and abatement costs (c); It falls with lower initial allocation of permits (N). Quite remarkably, the emission spot price at each instant $t \in [0, T]$ is bounded from above by the discounted penalty costs ($e^{-r(T-t)} \cdot P$) which may occur if the agent does not achieve compliance by the end of the regulated period.

With a precise focus on the European emission market and a distinction between long-term and short-term abatement measures, ? concentrate on the energy sector considering \mathcal{I} affected utilities which decide their abatement levels ($\xi_t^i, i = 1, \dots, \mathcal{I}$) at time $t \in [0, T]$ by relying on the cheapest

¹¹ u_t denotes the rate of abatement which is chosen by the representative agent.

possible abatement option in the short-term, i.e. the so-called fuel-switching (ζ_t^i).¹² Utilities can also trade emission permits (x_t^i). In particular, the authors characterize the evolution of the permit price (S_t) with respect to the developments of fuel prices (gas and coal) and demand of permits (Γ^i). Fehr and Hinz show that the equilibrium price of the emission permits is connected to the solution of a global control problem and is a function of the total demand for permits ($\Gamma = \sum_{i=1}^I \Gamma^i$) and of the aggregated pollution reduction ($\Pi = \sum_{i=1}^I \sum_{t=0}^{T-1} \xi_t^i$). The aggregation of the control variables - demand (Γ) and trading ($\sum_{i=1}^I x_t^i = 0$) of permits, and emissions reduction (Π) - makes the optimal solution of the global optimization problem equal to the optimal solution of a social planner, and most importantly eliminates the dependency of the permit price on the amount of permits traded at each instant. Therefore, the equilibrium price of the emission permits is given in terms of the permit demand and the optimal switching policy (ξ^*):

$$S_t = P \cdot \mathbb{E}_t [1_{(\Gamma - \Pi(\xi^*) \geq 0)}] \quad (5)$$

In the numerical section, Fehr and Hinz analyze the dependence of the permit price on the cumulated “relative” demand for permits (RD_t) and on the actual fuel-switching price ($\bar{\zeta}_t$).¹³ Although the permit price increases in both values, it changes significantly even with moderate variations of the cumulative “relative” demand. In contrast, the impact of the fuel-switching cost $\bar{\zeta}_t$ on the permit price is almost undetectable. Despite the loose relationship between emission permit price and fuel price changes, the authors claim that fuel-switching remains a fundamental factor. Finally, they investigate the important dependency of compliance probability and the price of emission permits on the penalty level and on the expected total demand for permits at the inception of the period. The authors show that, for a given “relative” aggregated demand of permits above a particular level, a rise in the penalty has on the one hand a strong and positive impact on compliance probability and, on the other hand, it does not increase the price of emission permits. It is worth noticing that, similarly to ?, the penalty P is still the upper limit of the permit price, i.e. $S_t \in [0, P]$.

All papers surveyed so far provide a fairly comprehensive treatment of the inter-temporal evolution of the permit price. However, such studies have been framed in a setting where fundamental aspects of trading permits, the strategic interaction among players, and the presence of asymmetric information in the market for permits were not taken into consideration. ? confirms that the market for permits does more than simply transfer permits from companies with a surplus in

¹²Fuel-switching involves the replacement of high-carbon (sulfur) fuels with low-carbon (sulfur) alternatives. The most common form of fuel switching in the U.S. is the replacement of high-sulfur coal with low-sulfur coal. In Europe, coal is typically replaced by natural gas. Therefore, ζ_t^i indicates the fuel-switching price process.

¹³The cumulated “relative” demand at time t is $RD_t = (\Gamma_t - \sum_{i=1}^I \sum_{t=0}^t \xi_t^i) / \lambda \cdot (T - t)$. This corresponds to the ratio between the net aggregated permits demand (aggregated permits demand minus the total pollution reduction up to time t) and the total minimum amount of emission reduction (λ) achievable by the end of the period T .

permits to companies with a deficit. This implies that emission permits are not only considered a compliance tool, but are also traded as “financial” contracts. More generally, fully transferable emission permits are not exclusively exchanged among relevant companies. For instance, individuals who may wish to retire permits, thereby denying their use to legitimize emissions, can participate in the market. Such opportunities underline the importance of understanding the aims of different market players, such as environmental groups, private citizens or pure speculators. ? is a first attempt in studying such an issue. However, the rest of the literature identifies investment and production-decisions of relevant companies as key drivers of the price formation of emission permits. ? belong to this group. That paper is similar in spirit to ? and ?. Unlike those two, ? develop an equilibrium model for the price dynamics of emission permits in the short term that accounts for strategic interactions in the market for permits in the presence of asymmetric information. In particular, the equilibrium price obtained for CO₂ emissions reflects the scarcity or excess of permits in the market. The authors consider \mathcal{I} firms who continuously emit offending gas (Q_t) according to a stochastic exogenous process over the period $[0, T]$. In particular Q_t evolves accordingly to a geometric Brownian motion

$$dQ_t/Q_t = \mu dt + \sigma dW_t.$$

Each firm i -th optimizes its cost functions at each instant $t \in [0, T - 1]$ adjusting the allocations of permits in their portfolios ($\delta_{i,t} = N_i + \sum_{s=0}^t x_{i,s}$) by choosing the optimal amount of permits to purchase ($x_{i,t} > 0$) or to sell ($x_{i,t} < 0$). Chesney and Taschini prove that at each instant t the equilibrium permit price (S_t) is a function of the penalty level (P) and of the individual expectations regarding not simply the aggregated, but the net accumulated pollution volumes of company i -th ($\int_t^T Q_{i,s} ds - \delta_{i,T-1}$) and of the other I^- companies, where $I^- := \mathcal{I} - i$.

$$S_t = e^{-\rho \cdot (T-t)} P \cdot \left\{ 1 - \mathbb{E}_t \left[\mathbf{1}_{\delta_{i,T-1} > \int_0^T Q_{i,s} ds} \right] \cdot \mathbb{E}_t \left[\mathbf{1}_{\delta_{I^-,T-1} > \int_0^T Q_{I^-,s} ds} \right] \right\} \quad (6)$$

Equation (??) is similar to (??), though in this framework pollution abatement options are not explicitly taken into account. In addition, the authors introduce asymmetric information imposing a one-time *lag-effect* on every firm. This implies that each firm i -th has complete knowledge about its own net accumulated pollution volume at time t

$$\int_0^t Q_{i,s} ds - \delta_{i,t-1}. \quad (7)$$

However, it does not have complete knowledge about the net accumulated pollution volumes of the others I^- firms covered by the regulations.

$$\int_0^{t-1} Q_{I^-,s} ds - \delta_{I^-,t-1}. \quad (8)$$

In sum, asymmetric information means that companies establish their permit trading strategies based on different information sets.

Though an explicit form of the permit price dynamics is not provided, its numeric evaluation has proven to be unproblematic. In the numerical section, the authors show that the equilibrium permit price is sensitive to the different characterizations of the pollution processes ($\{\mu, \sigma\} \in \mathbb{R}^{\mathcal{I}}$), and to the strategic purchases and sales of all relevant companies. Not surprisingly, the higher the expected pollution growths, the higher the probability of each firm being in shortage by the end of the trading period. In consequence, the permit price will also be higher. Similarly, the higher the uncertainty about each single net permit position before the compliance date, the higher the uncertainty about each probability of shortage. In consequence, the permit price will also be higher, again. The equilibrium permit price, in analogy with ? and ?, cannot be higher than the penalty level though, i.e. $S_t \in [0, P]$. Furthermore, in line with ?, ? and most recently ?, it is evident that the initial allocation of permits ($\mathbf{N} \in \mathbb{R}^{\mathcal{I}}$) plays a key role in the price formation of emission allowances. Finally, anticipating the importance of the development of derivative contracts in the markets for emission permits, Chesney and Taschini address the question as how to price CO₂-linked contracts. The importance of such a market is two-fold. First, option contracts satisfy the primary need of risk transfer from those who wish to reduce the risk of a permits shortage situation - namely the risk of financial exposure - to those willing to accept it. Allowing European companies covered by the EU ETS to reduce their exposure to emission price risk, buyers and sellers can better plan their businesses. Furthermore, any project-based investment, i.e. investments committed under the so-called CDM and JI mechanisms,¹⁴ and which at regular intervals return CO₂ emission reduction certificates yielding a payoff that depends on the CO₂ permit market price, can be considered as a (real) option contract. It is natural to interpret such projects as contracts whose value *derives* from the future CO₂ permit price. Similarly, any technological abatement investment or production process modification can be valued in terms of costs saved by purchasing emission permits or revenue from the sales of extra unused permits. In ? the authors address the question of pricing such option contracts.

Finally, we mention the paper of ?. Exploiting the arbitrage relationship existing in the EU ETS at the end of the first phase between CO₂ spot contracts and CO₂ forward contracts, the authors derive the dynamics of the spot price of the CO₂ emission permits. The authors

¹⁴It is worth mentioning that a part from emission permits, relevant companies can also use “certificates” acquired from outside the European Union, via the Joint Implementation (JI) or the Clean Development Mechanism (CDM) to meet their obligations under the EU ETS. Also the Kyoto protocol allows the utilization of so-called *flexible mechanisms*. Through JI, developed countries can receive emissions reduction units whenever they finance projects that reduce net pollution emissions in other developed countries. Through CDM, developed countries may finance GHG emission reduction or removal projects in developing countries, and receive credits for doing so. Interested readers may refer to the Intergovernmental Panel on Climate Change (IPCC) for relevant scientific, technical and socio-economic information related to these flexible mechanisms.

obtain such results by imposing an exogenous and arbitrary dynamics on the forward contracts. Though such a relation holds only when banking opportunities are not permitted (a situation which characterized in fact the transition time between the first and the second phase of the EU ETS), the pricing analysis performed under incomplete information is a promising area of research. It may stimulate further investigations and suggests new approaches for modeling the price formation of CO₂ emission permits in the present and future phases.

5 Conclusions

In contrast to the traditional command-and-control approach, marketable permits schemes accord significantly more freedom to regulated firms: No specific technology is required, and uniform emissions rate or percentage reduction is not imposed. Permits trading programs thus grant firms with low-cost methods of abatement an incentive to over-comply and sell their remaining permits to other firms which would otherwise have to face very costly pollution reductions. The result is a large diffusion of these marketable permits systems among policy makers and a consequent need to study the price formation of emission permits and to develop effective dynamic models for the price process. We discuss the theoretical results in environmental economics which are behind this popular policy measure and we then give an overview of the main factors that determine its effectiveness. Since price models are an essential component for constructing optimal hedging and purchasing strategies in a (GHG and carbon) constrained market, we analyze the recent papers which develop static and dynamic price models, taking into account banking and borrowing opportunities, pollution-abatement measures, strategic trading interactions and the presence of asymmetric information in the market for permits.

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