Three Essays on Prices vs. Quantities in Environmental Policy

Dissertation
zur Erlangung der Würde eines
Doktors der Staatswissenschaften

vorgelegt der
Wirtschaftswissenschaftlichen Fakultät
der Universität Basel

von
Iris Oberauner
von Österreich

Basel, 2012

Genehmigt von der Wirtschaftswissenschaftlichen Fakultät der Universität Basel auf Antrag von Prof. Dr. Frank C. Krysiak und Prof. Dr. Rolf Weder.

Basel, den 24. August 2012

Der Dekan: Prof. Dr. George Sheldon

Acknowledgements

The time I spent at the University of Basel was not simply employed in doing a job or writing my thesis, it was a time full of social and emotional experiences. Sometimes, it was frustrating, busy, and even annoying, but I would not want to have missed one moment of the past several years: most importantly due to the support and encouragement of certain people. It is therefore with great pleasure that I have the opportunity to express my sincere gratitude to all these people with the following words.

I am truly indebted and thankful to my supervisor, Frank C. Krysiak, for his enlightening guidance, inspiring ideas, constructive criticism and support in the areas of my daily routine. I thank him for opening up the whole spectrum of academic and university life to me and, in particular, for giving me the opportunity to write a joint paper with him, for making valuable suggestions regarding my research, and for teaching me how to present my work in talks.

I am very thankful for having had Rolf Weder as the second supervisor of my thesis: He is a positive, honest, and loyal person with a strong commitment to university concerns. I thank him specifically for his motivating support and encouragement.

The support and assistance of some people and institutions enabled me to carry my professional responsibilities in my daily routine. I would like to acknowledge the financial support of the University of Basel and of the Supporting Association of the Center of Economic Sciences. From the latter institution, I am especially grateful to Brigitte Guggisberg, to Michael Braune-Krickau, and to Christine Bracher. For kind assistance in administrative and job-related concerns, I am grateful to Sibylle Bösch, Yvonne Mery, Monika Ruckstuhl and Sandra Viehmeier. Special thanks go to Hermione Miller-Moser for proof-reading my thesis and helping me to formulate my thanks in English. I thank Stefan Vannoni, Lukas Mohler, Patrick Koch and Dominik Hauri from the Institut für Wirtschaftsstudien Basel for providing me with a workspace to finish my thesis and a pleasant working environment.

Your office colleagues have a strong influence on your mood and productivity in your daily routine. I really enjoyed sharing my office with Stefan Csordas, Simone Wyss and Lukas Tschabold, and more than that, I enjoyed our coffee breaks, lunches, controversial discussions, and entertaining evenings.

The time at the University of Basel was made enjoyable in large part due to the colleagues who became friends. I greatly value their friendship and I deeply appreciate their continuous encouragement and belief in me. In particular, I am eternally grateful to my three beloved girls: Meike Strasser for saving me and the world, Isabel Schmidt for being my sun, and Linda Walter, my role-model in toughness and reliability. In addition, I thank Matthias Gubler: If he were Calvin (if he isn't actually), I would like to be Hobbes. Furthermore, I am grateful to Yvonne Mery for being my solid and charming Austria connection as well as to Jürgen Schwarz, whose kind and considerate personality I really appreciate.

There is somebody who enriched my life in many ways over the past five-and-a-half years: from supportive collegiality to true friendship that turned into love. This is Lukas Mohler, and I would like to emphasize my deepest respect and admiration for him. I adore his professional competence, his honesty and loyalty, and foremost his amiable character. Thanks for loving me, believing in me more than I do, and all the memorable moments – and, hopefully, lots of them will follow.

Finally, I want to express my deepest love and thanks to the constants in my life: my parents, Maria and Anton Oberauner, and my sisters Martina Oberauner and Verena Schickl. How privileged I am to be part of this family. None of this would have been possible without their unconditional love, patience, encouragement and support in all my pursuits. To them I dedicate this thesis.

Contents

Preface **1**

Executive Summary and Principal Conclusions **7**

I Environmental Policy à la Carte:
Letting Firms Choose their Regulation
by Frank C. Krysiak and Iris Maria Oberauner **11**

I.1 Introduction 12
I.2 Review of the Literature 14
I.3 The Model 17
I.4 The Optimal Policy 20
I.5 Conclusions 33
I.6 References 35

II Prices vs. Quantities:
An Empirical Study of Firms' Instrument Choices
by Iris Maria Oberauner **37**

II.1 Introduction 38
II.2 Related Literature 39
II.3 Swiss Climate Policy Design 41
II.4 Theoretical Model 43

II.5 Data and Variables 47
II.6 Results and Discussion 51
II.7 Conclusions 58
II.8 References 60
II.A Appendix 63
II.A.1 Industry Classes 63
II.A.2 Descriptive Statistics 64
II.A.3 Results from a Freedom-of-Choice Estimation 65

III Abatement Technology Adoption under Different Policy Regimes: Some Empirical Evidence
by Iris Maria Oberauner **69**

III.1 Introduction 70
III.2 Related Literature 72
III.3 Swiss Climate Policy Design 73
III.4 Data and Variables 75
III.5 Results from a Bivariate Analysis 77
III.6 Results from a Multivariate Analysis 81
III.7 Conclusions 90
III.8 References 92
III.A Appendix 95
III.A.1 Variables Used in the Empirical Analysis 95
III.A.2 Firms' Choices and Econometric Models 96
III.A.3 Summary Statistics of Variables Used in the Multivariate Analysis 97
III.A.4 Multivariate Analysis in Logs 98

Curriculum Vitae **101**

List of Figures

I.1 The timing of decisions in our model. 18

I.2 The firms' choice of instrument as a function of their technologies. . . . 21

I.3 Policy à la carte vs. hybrid regulation. 32

I.4 Comparison of our approach with an optimally designed hybrid regulation in a numerical example. 33

II.1 Distributions of firms' employees in the FSO survey and the response sample. 48

II.2 Distributions of firms' industry affiliations in the FSO survey and the response sample. 48

II.3 The probability of choosing emissions trading conditional on the emissions intensity for various levels of the wage intensity. 56

II.4 The probability of choosing emissions trading conditional on the wage intensity for various levels of the emissions intensity. 56

II.5 The probability of choosing emissions trading conditional on the emissions intensity with restricted and unrestricted freedom of choice. 66

II.6 The probability of choosing emissions trading conditional on the wage intensity with restricted and unrestricted freedom of choice. 67

III.1 Firms' intensities of investments in CO_2 abatement technologies. 78

III.2 Effects of climate policy on investments in CO_2 abatement technologies. 79

III.3 Firms' choices and econometric models. 96

List of Tables

II.1 List of variables. 49

II.2 Logit regression for instrument choice. 53

II.3 NOGA 2008 General Classification of Economic Activities. 63

II.4 Descriptive statistics conditional on model specification. 64

II.5 Logit regression for instrument choice with freedom of choice. 65

III.1 Investment intensities in percent: Median, mean and Wilcoxon rank-sum test. 77

III.2 Investment- and R&D-related effects of climate policy implementation: Median and Wilcoxon rank-sum test. 79

III.3 Estimation results for the intensity of investments in CO_2 abatement technologies with the investment intensities modeled in levels. 84

III.4 Latent variable and unconditional marginal effects for Tobit and STP regressions in levels with discrete changes of the dummy variables. . . . 85

III.5 List of variables. 95

III.6 Summary statistics for the Tobit model in levels and logs and for the Probit model. 97

III.7 Estimation results for the intensity of investments in CO_2 abatement technologies with the investment intensities modeled in logs. 98

Preface

The thesis provides three essays on prices versus quantities in environmental policy – a leading topic in current environmental economics research. There is broad consensus in the community of academic economists that market-based instruments are superior in regulating harmful emissions. Therefore, the thesis focuses on the choice between a tax (*price* instrument) and a system of tradeable permits (*quantity* instrument).

Recently, policy instrument choice has gained particular attention in the context of climate change. Policy designs for greenhouse gas mitigation increasingly envisage market-based instruments. The most prominent example is the climate policy implemented by the European Union, which uses an emissions trading system to regulate greenhouse gases (EU ETS). By contrast, the Swiss Confederation implemented a mixed policy with a tax on carbon dioxide emissions and an emissions trading system at the same time, and it is left to the regulated firms to choose between these instruments.

Limited information of economic agents makes the choice between a tax and tradeable permits very important. In particular, uncertainty and asymmetric information impede first-best outcomes and induce diverging welfare losses under the instruments. An in-depth knowledge of the impacts of the policy instruments and their (perhaps superior) hybrid forms – static and dynamic as well as theoretical and empirical – is crucial to policy makers. This thesis contributes to enhancing this knowledge.

Existing research on prices vs. quantities in environmental regulation provides a solid foundation of analytical work on the performance of various regime designs (static and dynamic), which takes into account various sets of market imperfections (e.g. uncertainty) and incorporates the specific attributes of different pollutants (e.g. stock vs. flow pollutants). This thesis focuses on the aspects of this body of research that draw a good picture of the conditions observed in practice, that are widely accepted and recommended by environmental economists, and that are highly relevant for policy makers. First of all, *market-based instruments* – and specifically a tax and a system of tradeable permits – are considered. It is well known that incentive-based instruments are superior in terms of cost effectiveness. Second, *uncertainty and asymmetric information* are taken into account. These market imperfections are persistent issues in practice and should not be neglected when deriving normative prescriptions. Third, *normative analysis* is accompanied by *positive analysis*; theoretical results are verified by empirical evidence. Finally, carbon dioxide emissions are considered in empirical analysis, a pollutant to which particular attention has been devoted since the disclosure of anthropogenic *climate change*.

Differences in the performance between a price and a quantity instrument in environmental regulation are essentially attributable to three market characteristics that we can observe in practice: (1) Firms are different (firm heterogeneity); (2) they are exposed to uncertainty in many respects; and (3) they are usually better informed about their business than the regulatory authority (i.e. we observe information asymmetry).

With uniformity of firms and perfect information, instrument choice concerns would not arise: Under such circumstances, all firms exhibit equal costs in abating their emissions and the regulatory authority sets a policy in a way that every firm internalizes its external costs. Thereby, the costs for the society (i.e. firms' compliance costs plus environmental damages) are minimized. The cost-efficient outcome can equivalently be achieved by an emissions tax, an emissions subsidy, a system of tradable permits or a performance standard. However, in practice, we do not observe these ideal conditions.

Relaxing the homogeneity assumption, the regulator does best by specifying a market-price (tax) or the quantity (cap) for emissions, while market forces ensure cost effectiveness, i.e. marginal abatement costs are the same for all firms. Both instruments, the emissions tax and the system of tradeable permits, lead to an equivalent amount of emissions, to equal emission prices and to equal costs for the society.

The debate on instrument choice in environmental regulation gained particular attention with the seminal paper "Prices vs. Quantities" by Weitzman (1974), published in The Review of Economic Studies. Given uncertainty in abatement costs, he derived a formal criterion for the choice between a single-tax and a single-standard regime. It is reasonable to assume abatement cost uncertainty as, for example, factor prices and output demand are subject to (substantial) fluctuations in practice. While Weitzman's criterion is based on homogeneous firms, Williams (2002) derives the criterion by allowing for heterogeneity, thereby reducing the set of recommended instruments to a tax and permit trading (benefits of emission trading compared to a uniform standard arise from differences in firms' marginal abatement costs). While uncertainty drives expected damages under a tax (the emissions quantity adjusts ex post to the ex ante fixed price), it drives expected compliance costs under a system of tradeable permits (the permit price adjusts ex post to the ex ante fixed quantity). A tax is therefore the preferred instrument when marginal damages are flat relative to the industry's marginal abatement costs. Otherwise, an emissions trading scheme leads to lower expected social costs.

As an alternative to a single instrument regime, the regulatory authority can even use the flexibility of both instruments by regulating one part of the market with a tax, while the other part is regulated with emissions trading. Such a mixed policy is proposed by Mandell (2008). He shows that using both instruments simultaneously reduces expected social costs compared to a single tax and single permit trading. But, information on firms' abatement cost structure is required to optimally assign firms to the instruments. Although both the regulator and the firms face uncertainty in practice, firms are better informed about their actual costs to comply with the policy. Firms do not have an incentive to report this private information, so there is asymmetric information.

Uncertainty and imperfect information are important considerations in environmental regulation in practice, and both are concerns that have not yet received consideration – in combination – in the theoretical research on instrument choice between a tax and tradeable permits. The essay *"Environmental Policy à la Carte: Letting Firms Choose their Regulation"* fills this gap in the theoretical literature. An innovative approach is presented, in which the regulator implements a policy menu that consists of an emissions tax and a system of tradeable permits among which firms choose their preferred instruments. It is shown that it is welfare improving to delegate instrument choice to those agents that are better informed. By anticipating firms' instrument choices, the regulatory authority designs the policy in a way such that firms have an incentive to choose the instrument that is optimal from a social perspective. With this Policy à la Carte, the same expected social costs as Mandell (2008) can be attained. Thus, by letting firms choose the instrument, the asymmetric information problem can be overcome.

Besides static efficiency criteria, environmental policies should be evaluated in terms of the incentives they provide to promote technical change, i.e. in enhancing dynamic efficiency. Under a standard, firms do not have an incentive to overcomply with their target. Under a tax or permit trading, firms have a continuing incentive to reduce their emissions when the market provides worthwhile technological solutions that reduce the costs firms incur in complying with the policy. Environmental economics literature provides a variety of theoretical rankings for the most important environmental policy instruments in encouraging firms to adopt an advanced abatement technology. Examples of such studies are those by Milliman and Prince (1989), Jung et al. (1996), and Requate and Unold (2003). In the theoretical literature, emission taxes are typically the preferred alternative to free permits. An advanced abatement technology lowers firms' marginal abatement costs, leading to a lower market price for permits and, in turn, to lower incentives to adopt the new technology under free permits.

There is a comprehensive theoretical literature on prices vs. quantities in environmental policy. However, implementing environmental policy requires empirical studies to verify whether the instruments have the intended effects in practice and whether economic agents behave as suggested by the theory. Unfortunately, empirical studies in this research context are rare, first and foremost due to data limitations. Ideally, empirical analysis refers to an economy with at least two policy instruments implemented under similar economic conditions. Such a policy framework is typically not implemented in practice. But, the exceptional nature of the greenhouse gas mitigation strategies implemented in Switzerland by January 2008 offers an outstanding and worldwide unique policy framework to investigate research questions in the context of prices vs. quantities in environmental regulation. The Swiss Confederation offers firms a policy menu that consists of a tax and an emissions trading scheme from which they can choose their preferred instrument. So, a Policy à la Carte is implemented as theoretically analyzed in the first essay.

Swiss climate policy therefore provides an excellent opportunity to evaluate firms' instrument preferences within the Policy à la Carte framework and to verify whether firms behave as suggested by the theory. Furthermore, Swiss climate policy provides ideal conditions for comparative analysis on the relative performance of an emissions tax and a system of tradeable permits. First and foremost, the differential impacts of the instruments in promoting technological change, is a field of empirical research that is of particular interest for policy makers in designing current environmental policies and specifically in the context of fossile energy use and greenhouse gas mitigation strategies.

The first empirical research question is addressed in the second essay *"Prices vs. Quantities: An Empirical Study of Firms' Instrument Choices"*. In applying the specific design elements of Swiss climate policy, i.e. wage-based refunds of the tax receipts for taxpaying firms and free permits with a permit allocation that is based on historic emissions, a formal decision criterion for firms' instrument choices is derived. Theory identifies the driving forces for instrument choice as being permit allocation, wages, uncertainty in abatement costs and the flexibility of firms' abatement technologies. Empirical evidence confirms the influence of the former two aspects. By contrast, uncertainty and technological flexibility do not affect firms' instrument preferences. Based on the empirical results, uncertainty is revealed as not being crucial when firms chose the instrument themselves.

The second empirical research question is addressed in the last essay *"Abatement Technology Adoption under Different Policy Regimes: Some Empirical Evidence"* and is therefore the first study to provide insights into this topic. The analysis compares investment expenditures under a tax regime with those under a permit trading regime, thereby taking into account that there might be a self-selection bias due to firms' instrument choices. The result of the empirical analysis is unequivocal: Compared to a tax, free permits provide stronger incentives for technology adoption, i.e. in enhancing dynamic efficiency, a result which is the exact opposite of the traditional view in the theoretical literature brought forward, for example, by Milliman and Prince (1989) and Jung et al. (1996).

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Executive Summary and Principal Conclusions

In three essays, the debate on prices vs. quantities in environmental regulation is addressed and further developed – theoretically and empirically. First, an environmental "Policy à la Carte", a regulation that simultaneously employs an emissions tax and a system of tradeable permits among which firms can choose their preferred instrument, is theoretically analyzed. Second, the preferences of firms for the instruments is empirically tested under this policy regime. Third, the differential impacts of an emissions tax and permit trading on abatement technology adoption is investigated empirically.

While the performances of single and hybrid instruments are well analyzed in the literature, a Policy à la Carte has not been investigated so far. The simultaneous use of two market-based instruments with the instrument choice delegated to the regulated firms makes this policy design special. The Swiss Confederation implemented such a policy to mitigate carbon dioxide emissions. Under this design, firms can usually choose between paying a tax on their carbon dioxide emissions and participating in a system of tradeable permits. In the former case, they receive a wage-based refund of the tax receipts; in the latter case, they receive free emission allowances based on grandfathering.

The first essay *"Environmental Policy à la Carte: Letting Firms Choose their Regulation"* analyzes the Policy à la Carte regime theoretically. The three key assumptions are firm heterogeneity, uncertainty in marginal abatement costs, and information asymmetry between the regulator and the firms regarding their abatement technologies. The regulator offers firms a policy menu that consists of a tax and tradeable permits among which firms choose their preferred instrument. She anticipates that firms choose the instrument under which they expect lower costs and sets the tax rate and the cap accordingly. Furthermore, she grants a tax refund and/or auctions off parts of the permits. The latter two fine-tuning elements ensure that firms choose the instruments that are optimal from a social point of view.

A single-instrument policy (single tax or single permit trading) fails to provide a first-best outcome under uncertainty. The slope of the marginal abatement cost function relative to the slope of the marginal damage function determines the preferability of either instrument. Using both instruments simultaneously (mixed policy) reduces the welfare loss that arises from uncertainty when firms are optimally assigned to either the tax or permit trading. Therefore, the regulator requires information on firms' abatement technology. Firms do not have an incentive to report this information. It is shown that the asymmetric information problem can be overcome by delegating the prices-versus-quantities decision to firms. In this case, those agents choose the instrument who are better informed, thereby signalling abatement cost information to the regulator. Under limited information, a Policy à la Carte is then not only preferable to an optimally designed single-instrument policy, but it performs even as good as a mixed policy in which the regulator assigns the instruments to firms when she knows the firms' abatement technologies. Furthermore, even firms benefit from the option of being able to choose between the instruments. Besides, the policy is comparatively simple to implement.

The second and the third essay both provide empirical research on prices vs. quantities in a way that has not been brought forward so far in the literature. Empirical analysis is applied to an economy where both an emissions tax and permit trading are implemented to regulate harmful emissions. So, instrument-related effects can easily be determined. These unique and ideal conditions are currently provided by Swiss climate policy. Therefore, data from Swiss manufacturing firms were collected.

Based on these data, the second essay *"Prices vs. Quantities: An Empirical Study of Firms' Instrument Choices"* investigates firms' preferences between paying a tax and participating in permit trading within the Swiss Policy à la Carte regime. Based on the theoretical model of the first essay and by taking into account specific characteristics of the Swiss policy, a formal decision criterion for firms' instrument choices is derived. The theory identifies the influential factors for instrument choice as being the potential allocation with free permits, the potential refund of tax receipts, uncertainty in abatement costs, and the flexibility of firms' abatement technologies. Empirical evidence can be put forward with respect to the permit allocation and the tax refund: The propensity to choose emissions trading rises with the allocation with free permits, while firms' prefer the tax, when they expect a high tax refund. Both effects are statistically significant and robust. By contrast, uncertainty and flexibility do not have an effect on instrument choice. This may be attributed the fact, that Swiss firms are not only subject to price uncertainty in the permit trading regime, but also in the tax regime. Based on national emission reduction achievements, the tax rate may be increased in subsequent years. Thus, from a firm perspective, uncertainty is not an issue in instrument choice.

Firms' instrument choices are further driven by their abatement activities. This may be attributable to the banking of permits beyond the Kyoto period. Altogether, the empirical model has an outstanding high predictive power: Predicted instrument choice corresponds to observed choice for 87.5 percent of the firms considered. Moreover, only little information is required about firms in order to predict their preferences between a tax and permit trading correctly with a high degree of probability.

In the last essay *"Abatement Technology Adoption under Different Policy Regimes: Some Empirical Evidence"* empirical analysis focuses on the differential impacts of an emissions tax and permit trading on the adoption of abatement technologies. To analyze the research question, bivariate analysis is accompanied by multivariate analysis. The outcome of interest is the intensities of investments in abatement technologies of Swiss firms to indicate technology adoption. With the unique design of Swiss climate policy, a binary variable could be constructed – indicating policy regime affiliation – in order to identify any instrument-related effects in firms' adoption behavior.

In the bivariate analysis, significantly higher incentives to adopt advanced abatement technologies can be observed for firms participating in emissions trading. In the multivariate analysis, results are obtained from a three-pronged estimation procedure: (1) OLS model, (2) Tobit model, and (3) simultaneous Tobit-Probit model with the third taking into account the possibility that there might be a self-selection bias due to firms' instrument choices. Furthermore, all three models are estimated with the investment intensities modeled in levels as well as in logs. The multivariate analysis yields a qualitatively robust effect: Compared to the tax, firms' investments in advanced abatement technologies are significantly higher under free permits. It has to be noted, however, that the multivariate analysis suffers from small sample size and crucial econometric model assumptions are violated.

From the bivariate and the multivariate analysis, the following general conclusion can be drawn: Irrespective of the statistical method used to analyze the data, the results indicate the superiority of free permits in providing incentives to adopt advanced abatement technologies. This result is the direct opposite of the traditional view in the theoretical literature according to which a tax would provide higher incentives for technology adoption. Differences in the perceived stringency of the instruments, uncertainty and transition effects of policy implementation may be reasonable arguments for the observed effect. Despite statistical weaknesses, the essay provides the first empirical study on the relative performance of a tax and free permits in enhancing dynamic efficiency.

The thesis contributes to the environmental economics literature by providing an innovative approach (Policy à la Carte) to regulate harmful emissions that takes into account market imperfections that can be observed in practice (uncertainty and asymmetric information). Moreover, empirical research in the context of the prices-vs.-quantities debate is brought forward that could only be conducted due to the unique design of Swiss climate policy. Under equal economic conditions, a tax and a permit trading scheme are implemented at the same time. From this research, valuable insights can be gained for policy makers by providing evidence on how firms actually respond to environmental regulation in practice. Currently, the Swiss policy framework offers outstanding conditions for empirical research on prices vs. quantities. However, changes in legislation indicate that this may not last forever.

Essay I

Environmental Policy à la Carte: Letting Firms Choose their Regulation[1]

Frank C. Krysiak

University of Basel, Faculty of Business and Economics, Department of Environmental Economics, Peter Merian-Weg 6, 4002 Basel, Switzerland, *Frank.Krysiak@unibas.ch*

Iris Maria Oberauner

University of Basel, Faculty of Business and Economics, Department of Environmental Economics, Peter Merian-Weg 6, 4002 Basel, Switzerland, *Iris.Oberauner@unibas.ch*

Abstract

Under uncertainty, the optimal choice between price and quantity instruments depends on the technology of the regulated firms, which is often private information. We consider an environmental policy that delegates the prices-versus-quantities decision to the firms by offering them the choice between an emissions tax and permit trading. Such an approach is currently used in Swiss climate policy. We provide a detailed characterization of the optimal policy and show that this approach reduces expected social costs compared to a pure tax or permit-trading regime. We demonstrate that an optimal allocation of firms to instruments can be achieved despite substantial informational constraints, and that all firms gain from the introduction of the instrument choice compared to optimally designed single-instrument policies. Furthermore, we discuss the conditions under which this approach is likely to be preferable to a hybrid regulation.

Keywords: Environmental Policy, Asymmetric Information, Screening, Uncertainty, Prices-versus-Quantities

JEL classification: Q58, D82, H23, D81, Q54

[1]Published in the *Journal of Environmental Economics and Management*, 60 (2010) pp. 221–232.

I.1 Introduction

The literature on environmental policy design typically assumes that the policy instrument faced by a firm is dictated by the regulator. The regulator levies a tax, sets a standard, or implements a permit market, and the firms decide on production and abatement under the incentives set by this policy.

This "top-down" type of policy performs well under perfect information. However, whenever the policy is not continuously adjusted to cost shocks, it can implement only a second-best allocation under information constraints like asymmetric information or uncertainty (Weitzman, 1974). Welfare losses arise, because the policy implements an ex-ante fixed quantity or price of emissions and thus almost surely fails to equalize marginal abatement costs and marginal damage ex post.

Information constraints are ubiquitous in practice. In many cases, limited predictability of future factor and product prices results in uncertainty. Also, firms usually have better knowledge about their abatement costs than a regulator, so that there is asymmetric information with regard to the firms' technologies.

Two classes of approaches have been developed that can eliminate or reduce the accruing welfare losses. The first class comprises approaches where the policy is adjusted to firm behavior, such as open market operations analyzed in Krysiak (2008a) (which can combat uncertainty) or incentive schemes as shown by Collinge and Bailey (1983) (which counter asymmetric information). These approaches require frequent and timely governmental action or rather complex policy designs and are consequently rarely used in environmental policy. The second class relies on approaches where the policy is fixed ex ante. These approaches are more easily implementable but can only reduce, not eliminate, the welfare losses attributable to information constraints. Among these are hybrid and mixed instruments. Hybrid instruments, as proposed by Roberts and Spence (1976), alleviate welfare losses by using differing instruments for different realizations of cost shocks. Mixed instruments, as shown by Mandell (2008), reduce welfare losses by using different instruments for different firms. Both approaches focus on reducing the social costs of uncertainty.

Instrument combinations build on the insight of Weitzman (1974) that, under uncertainty, the optimal choice of a policy instrument depends on firms' technologies. If firms differ with regard to their technologies, it can be optimal to regulate them with different instruments. Depending on their technologies, firms are assigned to a price-based instrument (tax) or a quantity-based instrument (permit trading). This approach is of particular importance in climate policy, where many countries regulate different sectors with different instruments.

In this paper, we take the approach of instrument combination a step further by considering not only cost uncertainty and firm heterogeneity but also asymmetric information with regard to the firms' technologies. This is relevant in many applications, where the regulating authority does not have full information about each firm's technology. Without this information, the assignment of firms to instruments cannot be made by the regulating authority.

To solve this problem, we decentralize the instrument choice. The idea is that the power of market-based instruments compared to command-and-control policies lies in granting the regulated firms the opportunity to choose their emissions, as they have better information concerning their abatement costs. The regulating authority only sets incentives for abatement. Under uncertainty, not only individual abatement decisions but also the choice between price and quantity instruments matters (Weitzman, 1974), and the optimal instrument choice depends on firm-specific information (its technology). Thus it seems reasonable to grant firms the right to choose not only their abatement efforts but also the instrument with which they are regulated. The regulatory authority only sets incentives to assure that the firms' choices are socially optimal.

In our approach, the regulator offers firms a menu of policy instruments that consists of permit trading and an emissions tax. Each firm chooses one of these instruments and is then regulated for several periods with this instrument. To assure a socially desirable allocation of firms to instruments, the regulator can fine-tune the policy menu by auctioning some of the permits or by giving a lump-sum transfer (or a partial tax exemption) to the tax-paying firms. The regulator does not know which firm uses which technology, so that there is asymmetric information. Furthermore, firms (as well as the regulator) do not have full information about their future abatement costs when choosing a policy instrument (e.g., due to uncertain future factor prices or uncertain future demand), so that there is also uncertainty.

This approach differs from previous incentives schemes, such as Collinge and Bailey (1983), in that we consider both asymmetric information and uncertainty. In addition, we constrain our analysis to policies that do not need to be adjusted to cost shocks. This rules out incentive schemes, such as the Vickrey auction considered in

Collinge and Bailey (1983).[2]

There are three motivations for investigating the above regulatory setting. First, we want to inquire whether the welfare gains characterized in Mandell (2008) can be realized with less demanding information requirements, and thus for a broader range of applications. Second, the question of whether instrument choice can be delegated to the regulated firms is conceptually interesting. Finally, a self-selection approach, similar to the one that we consider, has been recently implemented in Switzerland, where firms can choose between paying a carbon tax or participating in an emissions-trading scheme.[3]

We show that under uncertainty and asymmetric information, it is welfare improving to delegate instrument choice to regulated firms. An optimal self-selection of firms can be achieved, and the menu from which the firms choose their preferred instrument is fairly simple. Despite the asymmetric information, the same expected social costs as in Mandell (2008) can be attained by the self-selection mechanism. Furthermore, compared to a single-instrument design, all firms gain from the ability to choose. We also show that a surprising result of Mandell (2008), that an optimal policy mix always includes the tax but not always emissions trading, holds in a setup with a more general form of firm heterogeneity. Finally, we compare our approach to the hybrid regulation of Roberts and Spence (1976).

I.2 Review of the Literature

Our study is related to the screening literature, to the literature on incentive schemes for pollution control, and to the prices-versus-quantities literature.

In the screening literature, a set of contract options is considered as a screening device in markets with asymmetrically distributed information (Riley, 2001; Stiglitz, 1977). Insurance companies, for example, often offer a set of contracts from which their clients choose according to their private information. The standard setting results in a separating equilibrium when two groups of risk types are considered, and markets are competitive. Thus private information can be revealed by self-

[2]Adjustments in the form of open market operations are necessary for using the Vickrey auction in cases where costs change unexpectedly (Collinge and Bailey, 1983). In many applications, such changes occur frequently, e.g., due to varying demand or volatile factor prices. Thus frequent governmental action would be necessary to use this incentive scheme in such cases.

[3]A similar approach has also been used in the UK (Smith and Swierzbinski, 2007).

selection.

In environmental economics, similar mechanisms have been analyzed. In a setup with asymmetric information but no uncertainty, incentive schemes can be found that render it optimal for firms to reveal private technological information (Collinge and Bailey, 1983; Dasgupta et al., 1980; Kwerel, 1977; Spulber, 1988). However, a regulation often has to be designed before actual costs are known and may not be adjusted frequently in response to cost changes, because such adjustments are subject to administrative delays, incur costs, and can induce inefficiencies due to strategic firm behavior (Moledina et al., 2003). In such a setting, firms have only a limited ability to reveal private information, as they do not have full information themselves at the time when the policy is promulgated. Also, the incentives for revealing information are changed, because firms know that the regulator cannot optimally react to their actions. Thus, under uncertainty, rather complex incentive schemes are necessary to elicit the private information necessary for an optimal regulation.

A special case with uncertainty and asymmetric information is investigated in Mentero (2000), where the optimal phase-in of a permit market is analyzed; some firms are obliged to participate in permit trading while participation is voluntary for others. An optimal opt-in rule is derived that allows information to be elicited from the voluntarily participating firms. However, the assignment of firms among instruments (compulsory and voluntary emissions trading) is given, whereas our focus is to find the optimal distribution of firms among different instruments.

The prices-versus-quantities literature, initiated by Weitzman (1974), analyzes the choice between a tax and a standard in a setting where the marginal abatement costs of the regulated firms are uncertain at the time when the regulation is designed. If the abatement cost function is strictly convex, expected abatement costs are lower with a price instrument, as firms have the opportunity to adjust their abatement efforts to the cost shocks. On the other hand, such adjustments induce varying emissions, which increases the expected damage whenever the damage function is strictly convex. Which of these effects dominates depends on the relative curvature of the abatement cost and damage functions.

Several studies have advanced policy designs that can improve on a simple price or quantity regulation. As shown by Roberts and Spence (1976), a hybrid regulation that consists of a permit market together with a price floor (set by a subsidy) and a price ceiling (set by a tax) can achieve a higher level of expected welfare than permit trading alone. Similar gains can be realized by issuing options for buying additional permits (Unold and Requate, 2001), by renting permits at prices that increase with the total number of permits (Collinge and Oates, 1982), or by adjusting the number of permits on a permit market over time (Henry, 1989; Newell et al., 2005).[4]

Closest to our study is Mandell (2008) who analyzed the combined use of a permit market and a tax. Firms have linear marginal abatement costs $c' = K + \varepsilon - e_i/\beta_i$, where e_i denotes firm i's emissions, and where ε is a common cost shock. Firms are heterogeneous with regard to the curvature of their cost function $(1/\beta_i)$. The regulator can observe the technology (the value of β_i) of each firm.

The main results of Mandell (2008) are that is it is often optimal to use both instruments simultaneously and that there is an asymmetry between them: It can be optimal to use only an emissions tax, whereas it is never optimal to use only permit trading.

The benefit of using two instruments simultaneously is that the difference between marginal abatement costs and marginal damage due to the cost shock is reduced; total emissions are closer to the ex-post efficient level than under a single instrument policy (reduced volume error). However, this comes at the cost of the marginal abatement costs of permit-trading firms (which vary with the cost shocks) differing from those of tax-paying firms (which always equal the constant tax), whenever a cost shock occurs. Therefore total abatement costs are not minimal (allocation error). Whenever the reduction in the volume error outweighs the allocation error, it is optimal to use both instruments.

The asymmetry arises because the reduction in the volume error due to using a mixed instrument is larger when the marginal damage function is steep compared to the marginal abatement cost function, in which case permit trading would be the preferable policy in a single instrument regime. In this case, the volume error reduction achieved by shifting a single firm to the tax always outweighs the increase in the allocation error. So it is never optimal to have only permit-trading firms. If the marginal damage function is relatively flat, in which case a tax would be preferable in a single instrument design, the volume error reduction achievable by using a mixed instrument can be outweighed by the increase in the allocation error. Therefore it can be optimal to have only tax-paying firms.

[4] A detailed discussion of these mechanisms is provided in Krysiak (2008a).

I.3 The Model

A fixed number of firms emit a homogenous and uniformly mixed pollutant, which causes environmental damage. Firms can reduce their emissions by abatement. There are different types of firms that use different technologies and thus have different abatement cost functions. A regulator sets an environmental policy to minimize expected social costs, which consist of the expected environmental damage and the firms' expected abatement costs.

The regulation is subject to information constraints. Future abatement costs are subject to random influences, like changing factor prices, demand-side shocks, or the breakdown of production equipment. This uncertainty exists both from the regulator's and from the firm's perspective. In addition, there is asymmetric information. The regulator knows which technologies exist but does not know which firms use which technology (Gottinger, 2001; Mentero, 2000). So, the regulator does not know how much flexibility a given firm has in adjusting its abatement to cost changes, which is the central technology parameter in the prices-versus-quantities decision (Weitzman, 1974).

This informational asymmetry is typical for many environmental policy settings. Often, some information on aggregate abatement costs exists owing to previous regulation or to impact studies. But detailed, disaggregate information is missing in many cases, such as the information as to how much flexibility a given firm has in adjusting its abatement.

To overcome the informational asymmetry, we use a model setup and timing as illustrated in Figure 1. In Step 1, the regulator offers the firms a choice between paying a tax and participating in emissions trading. In Step 2, each firm has to commit to one policy instrument for several periods before knowing its exact abatement costs in these periods. Therefore, firms will choose according to their expected costs. In each of the periods in Step 3, they observe their actual costs and optimize their abatement under the instrument that they have chosen. We assume that the realization of a firm's abatement costs are intertemporally independent, so that it suffices to consider only a representative period in Step 3.

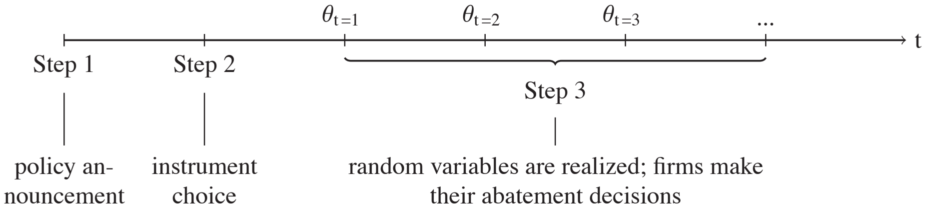

Figure I.1: The timing of decisions in our model.

To analyze this policy, we use the following variant of the prices-versus-quantities model of Mandell (2008); Weitzman (1974); Williams III (2002). There is a continuum of firms with mass one whose abatement cost functions can be approximated by

$$C(a, \beta, \theta) = (\alpha + \theta)a + \frac{a^2}{2\beta}, \tag{I.1}$$

where a denotes abatement, θ is a random influence, and $\alpha \geq 0$ and $\beta > 0$ describe a firm's technology.[5] We assume that the random influences are firm-specific but positively correlated among firms with a correlation coefficient $\rho \in (0, 1]$. Such correlation is typical for many applications, as regulated firms are subject to the same business cycles and similar movements of factor prices. For all firms, the expected value of θ is zero, and we denote its variance by $\sigma^2 > 0$.

The parameter α is identical for all firms but β varies among them (Mandell, 2008).[6] We assume that the distribution of the parameter β has a differentiable density $\phi(\beta)$ defined over $\beta \in [0, \infty)$ with $\phi(0) = 0$ and $\lim_{\beta \to \infty} \phi(\infty) = 0$. Thus only perfectly flexible and fully inflexible technologies are excluded from our analysis per se. Furthermore, the set of feasible technologies is connected, that is, if $\phi(\beta_1) > 0$ and $\phi(\beta_2) > 0$, then $\phi(\beta_3) > 0$, for all $\beta_3 \in [\beta_1, \beta_2]$. This implies that if two technologies are feasible, any combination of these technologies can be used as well. We denote the expected value of β by $\hat{\beta}$.

Only the density function $\phi(\beta)$, the cost function (I.1), and the variance of θ are known to the regulator. Our informational setup differs from that in Mandell (2008), where the regulator knows which firm uses which technology and assigns firms to

[5]For notational simplicity, we use the reciprocal of the second derivative of $C(a, \beta, \theta)$ as a technology parameter. Thus compared to the notation used in Weitzman (1974), we have $C'' = 1/\beta$.

[6]In many applications, firms' abatement costs will differ with regard to both parameters. But as we show in Section I.4, heterogeneity with regard to α does not change our results.

an instrument based on this information. Also, in Mandell (2008), a uniform distribution of β is used to model firm heterogeneity.

The emissions of a firm exerting abatement a are given by $e(\beta) = \bar{e} - a(\beta)$, where $\bar{e}$ denotes a firm's baseline emissions (i.e., firms' emissions in the absence of regulation).[7] Total emissions are $E = \int_0^\infty e(\beta)\phi(\beta)d\beta$. The environmental damage caused by pollution $D(E)$ is approximated by a quadratic function

$$D(E) = \gamma E + \frac{E^2}{2\delta}, \tag{I.2}$$

where $\gamma \geq 0$, $\delta > 0$ are constant parameters. To assure that an intervention is optimal at all and that it is not optimal to reduce total emissions to zero, we assume $\gamma \in (\alpha - \bar{e}/\delta, \alpha + \bar{e}/\hat{\beta})$.

The policy consists of three elements. First, the regulator grants z_q permits free of cost to each firm that participates in the emissions-trading scheme. Second, the regulator sets an emissions tax p_p. Granting some firms emission permits for free while demanding that other firms pay an emissions tax for all of their emissions can be seen as a lump-sum transfer to the permit-trading firms. Such a transfer would set a strong incentive to choose permit trading. To correct this, the regulator uses a third element, which can be either a partial auctioning of permits or a lump-sum transfer to the tax-paying firms. For notational simplicity, we model a transfer to the tax-paying firms as a (partial) tax exemption that is independent of a firm's actual emissions.[8]

The first two elements are standard. The third one serves to fine-tune a firm's choice between the policy instruments to assure that all firms choose the type of regulation that is best from a social perspective.

[7]We assume that baseline emissions are deterministic, as we use an abatement cost function that depends on abatement efforts. The marginal costs of reducing emissions below their baseline value is randomly varying, but, without environmental policy, firms always choose $a = 0$, so that this variation does not influence baseline emissions. In contrast, Mandell (2008) uses an abatement cost function that depends on emissions, so that optimal emissions in the absence of environmental policy are subject to random influences.

[8]Such an exemption is used, for example, in Swiss climate policy.

I.4 The Optimal Policy

We analyze the problem via backward induction. Consider a firm of type β that has opted to pay the emissions tax. In Step 3 this firm will minimize its total costs, given the tax p_p and the tax exemption z_p:

$$\min_{a\geq 0} \quad (\alpha+\theta)a+\frac{a^2}{2\beta}+p_p\left(\bar{e}-a-z_p\right). \tag{I.3}$$

This results in emissions $e_p(\beta,\theta)=\bar{e}-\beta\left(p_p-\alpha-\theta\right)$ and expected costs

$$\mathcal{E}\left(C_p(\beta)\right)=p_p\left(\bar{e}+\alpha\beta-z_p\right)-\frac{\beta}{2}\left(p_p^2+\alpha^2\right)-\frac{\beta}{2}\sigma^2. \tag{I.4}$$

As is apparent from Eq. (I.4), the firm benefits from the cost uncertainty. With constant abatement, the firm's expected costs would be independent of σ^2, because the cost function is linear in the random variable. By optimally adjusting its abatement, the firm can improve upon this and thereby reduce its expected costs. The more flexible is the firm's technology (higher β), the stronger this effect becomes.

A firm participating in the emissions-trading scheme will minimize the costs

$$\min_{a\geq 0} \quad (\alpha+\theta)a+\frac{a^2}{2\beta}+p_q\left(\bar{e}-a-z_q\right), \tag{I.5}$$

where z_q denotes the number of costlessly granted permits and where p_q is the endogenously determined market clearing price for permits. The optimal emissions of such a firm are $e_q(\beta,\theta)=\bar{e}-\beta\left(p_q-\alpha-\theta\right)$.

To determine the market clearing price for permits, we must first determine how firms self-allocate to the instruments. From a social perspective, the permit market should contain firms with a high β (and thus a low C'' in the notation of Weitzman (1974)) rather than those with a low β, because firms with a more flexible technology (high β) will adjust their output more strongly to cost shocks, which leads to higher expected damage. However, as Eq. (I.4) shows, a firm gains more from the greater abatement flexibility afforded by taxes if it has a more flexible technology. So with regard to instrument choice, the firm-level incentives stand in direct opposition to those of a social planner. Given that we investigate a self-selection mechanism, we have to accept the sorting that corresponds to the firm-level incentives and search for a policy menu that minimizes expected social costs under this restriction. This allocation of firms to instruments is depicted in Figure 2.

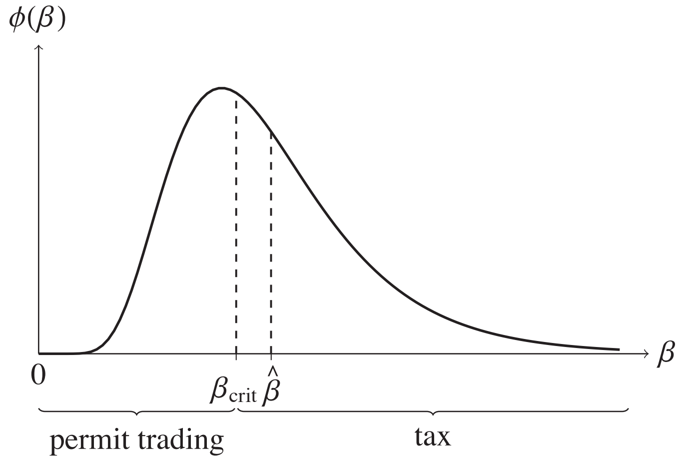

Figure I.2: The firms' choice of instrument as a function of their technologies.

Assuming that the policy is set in a way that, for a given $\beta_{crit} \geq 0$, all firms with $\beta \leq \beta_{crit}$ participate in the emissions-trading scheme, and all firms with $\beta > \beta_{crit}$ choose to pay the tax, the market clearing condition can be written as

$$\int_0^{\beta_{crit}} \left(e_q(\beta, \theta) - z_q - z_q^{auc}\right) \phi(\beta) d\beta = 0, \tag{I.6}$$

where z_q^{auc} denotes the number of auctioned permits per permit-trading firm. To present the following analysis compactly, we define $\mathcal{E}_a^b(1) = \int_a^b \phi(\beta) d\beta$ and $\mathcal{E}_a^b(\beta) = \int_a^b \beta\phi(\beta) d\beta$. Thus $\mathcal{E}_0^{\beta_{crit}}(1)$ denotes the fraction of firms participating in permit trading, whereas $\mathcal{E}_{\beta_{crit}}^{\infty}(1)$ is the fraction of firms regulated by the tax. The quantities $\mathcal{E}_0^{\beta_{crit}}(\beta)$ and $\mathcal{E}_{\beta_{crit}}^{\infty}(\beta)$ help to characterize the average technology of the tax-paying firms, which is $\mathcal{E}_{\beta_{crit}}^{\infty}(\beta) / \mathcal{E}_{\beta_{crit}}^{\infty}(1)$, and the average technology of the permit-trading firms, which is $\mathcal{E}_0^{\beta_{crit}}(\beta) / \mathcal{E}_0^{\beta_{crit}}(1)$. Note that, by definition, $\mathcal{E}_{\beta_{crit}}^{\infty}(1)$ and $\mathcal{E}_{\beta_{crit}}^{\infty}(\beta)$ are decreasing in β_{crit}.

With this notation, the market clearing price for emission permits is

$$p_q = \alpha + \left(\bar{e} - z_q - z_q^{auc}\right) \frac{\mathcal{E}_0^{\beta_{crit}}(1)}{\mathcal{E}_0^{\beta_{crit}}(\beta)} + \theta_{p_q}, \tag{I.7}$$

where $\theta_{p_q} = \int_0^{\beta_{crit}} \beta\theta\phi(\beta) d\beta / \mathcal{E}_0^{\beta_{crit}}(\beta)$ denotes the change of the permit price that is induced by the varying demand for permits resulting from the individual cost changes θ. Thus θ_{p_q} captures the influence of the cost fluctuations on the market clearing price for permits. Calculating θ_{p_q} shows that we have $\mathcal{E}\left(\theta_{p_q}\right) = 0$, $\mathcal{E}\left(\theta_{p_q}^2\right) = \rho\sigma^2$, and $\mathcal{E}\left(\theta_{p_q}\theta\right) = \rho\sigma^2$.

With Eq. (I.7), the expected costs of a permit-trading firm are

$$\begin{aligned}\mathcal{E}\left(C_q(\beta)\right) =&\alpha(\bar{e}-z_q)+(\bar{e}-z_q)\left(\bar{e}-z_q-z_q^{auc}\right)\frac{\mathcal{E}_0^{\beta_{crit}}(1)}{\mathcal{E}_0^{\beta_{crit}}(\beta)} \\ &-\frac{\beta}{2}\left(\bar{e}-z_q-z_q^{auc}\right)^2\left(\frac{\mathcal{E}_0^{\beta_{crit}}(1)}{\mathcal{E}_0^{\beta_{crit}}(\beta)}\right)^2-\frac{\beta}{2}(1-\rho)\sigma^2.\end{aligned} \tag{I.8}$$

Again, the firm benefits from the cost uncertainty (as can be seen from the last term of Eq. (I.8)). However, the gain is smaller than under taxes, as there is a positive correlation between a firm's abatement costs and the permit price, which reduces the firm's adjustments.

Given the expected costs under both instruments, we can now analyze which firms will choose which policy instrument. Comparing the expected costs under the tax regime (Eq. (I.4)) and under the permit-trading scheme (Eq. (I.8)) shows that the difference between these costs depends linearly on β. Thus, there can be at most a single type of firm (i.e., a single value of β) for which the expected costs under a tax equal those under permit trading. As in Figure 2, we denote the technology parameter of this indifferent firm by β_{crit}.

To derive the optimal policy set, we also need information concerning the total emissions and the resulting damage. Total emissions are

$$E=\bar{e}\mathcal{E}_{\beta_{crit}}^{\infty}(1)-(p_p-\alpha)\mathcal{E}_{\beta_{crit}}^{\infty}(\beta)+(z_q+z_q^{auc})\mathcal{E}_0^{\beta_{crit}}(1)+\theta_E, \tag{I.9}$$

where θ_E denotes the random variation of total emissions that is due to the random cost changes. Calculating θ_E shows that $\mathcal{E}(\theta_E)=0$ and $\mathcal{E}(\theta_E^2)=\rho\sigma^2\left(\mathcal{E}_{\beta_{crit}}^{\infty}(\beta)\right)^2$.

The expected environmental damage follows from substituting the total emissions (I.9) in the damage function (I.2) and calculating the expected value. As in Mandell (2008); Weitzman (1974); Williams III (2002), a price-based regulation leads to volatile aggregate emissions, which incurs social costs. This is true whenever $\mathcal{E}_{\beta_{crit}}^{\infty}(\beta)>0$, that is, whenever there are firms that choose the tax. Emissions then include a random component.

Denoting the expected total tax revenue by $\mathcal{E}(T)$ and the expected revenue from permit auction by $\mathcal{E}\left(T^{auc}\right)$, the optimal policy can be described by[9]

$$\min_{p_p,z_p,z_q,z_q^{auc}} \int_0^{\beta_{crit}} \mathcal{E}\left(C_q(\beta)\right)\phi(\beta)d\beta + \int_{\beta_{crit}}^{\infty} \mathcal{E}\left(C_p(\beta)\right)\phi(\beta)d\beta \tag{I.10}$$

$$+\,\mathcal{E}\left(D(E)\right) - \mathcal{E}\left(T\right) - \mathcal{E}\left(T^{auc}\right),$$

$$\text{s.t.} \quad \mathcal{E}\left(C_q(\beta_{crit})\right) = \mathcal{E}\left(C_p(\beta_{crit})\right) \quad \text{if} \quad 0 < \mathcal{E}^{\infty}_{\beta_{crit}}\left(\beta\right) < \hat{\beta}. \tag{I.11}$$

The following proposition characterizes the solution of this optimization problem.

Proposition 1. *The optimal menu of policies is given by*

$$p_p^* = \frac{\bar{e} + \alpha\hat{\beta} + \gamma\delta}{\hat{\beta} + \delta}, \tag{I.12}$$

$$z_q^* + z_q^{auc^*} = \bar{e} - \frac{\left(2\hat{\beta} - \delta\right)\left(\bar{e} - \delta(\alpha - \gamma)\right)}{2\left(\hat{\beta} + \delta\right)\left(1 - \mathcal{E}^{\infty}_{\beta_{crit}}\left(1\right)\right)}, \tag{I.13}$$

$$z_p^* = z_q - \rho\sigma^2 \frac{\beta^*_{crit}(\hat{\beta} + \delta)}{2\left(\bar{e} + \alpha\hat{\beta} + \gamma\delta\right)}. \tag{I.14}$$

Under this policy menu, the indifferent firm is implicitly characterized by

$$\mathcal{E}^{\infty}_{\beta^*_{crit}}\left(\beta\right) = \begin{cases} \frac{\delta}{2}, & \textit{for } \delta \leq 2\hat{\beta}, \\ \hat{\beta}, & \textit{otherwise,} \end{cases} \tag{I.15}$$

which yields a unique solution β^*_{crit}, whenever $0 < \delta < 2\hat{\beta}$. All firms with $\beta > \beta^*_{crit}$ choose the tax, whereas all firms with $\beta < \beta^*_{crit}$ participate in the emissions-trading scheme.

If $\delta < 2\hat{\beta}$, the reduction in expected social costs compared to an optimally designed permit market is $\rho\sigma^2\delta/8$, and it is $\rho\sigma^2(2\hat{\beta} - \delta)^2/(8\delta)$ compared to an optimally set emissions tax.

Proof. Calculating the derivatives of the expected social costs specified in (I.10) with respect to p_p, z_q, z_q^{auc} leads to a linear equation system with rank two and the solutions (I.12)–(I.13). The expected social costs are independent of z_p, and, for $p_p > 0$, Eq. (I.11) is an implicit surjective mapping of $z_p \in \mathbb{R}$ to $\beta_{crit} \in [0, \infty[$. Thus

[9] The constraint (I.11) is binding, whenever both instruments are in use. In this case, there is an indifferent firm whose technology characterizes the firms' instrument choices.

we can optimize (I.10) with respect to β_{crit} instead of z_p and get (I.15). By our assumptions on $\phi(\beta)$, $\mathcal{E}^{\infty}_{\beta_{crit}}(\beta)$ is a strictly monotonic function of β_{crit}, whenever $0 < \mathcal{E}^{\infty}_{\beta_{crit}}(\beta) < \hat{\beta}$ and thus, by (I.15), whenever $0 < \delta < 2\hat{\beta}$. Therefore, (I.15) has a unique solution under this condition.

If $\delta \leq 2\hat{\beta}$, then the Hessian of the expected social costs with regard to (p_p, z_q, z_q^{auc}, β_{crit}) is locally positive definite at (I.12), (I.13), and (I.15), so that these values indeed induce minimal expected social costs. If $\delta > 2\hat{\beta}$, then we have a boundary optimum at $\mathcal{E}^{\infty}_{\beta^*_{crit}}(\beta) = \hat{\beta}$, which implies that no firm chooses permit trading.

Eq. (I.14) follows from solving Eq. (I.11) under (I.12) and (I.13). That all firms with $\beta > \beta^*_{crit}$ choose the tax, whereas all firms with $\beta < \beta^*_{crit}$ choose emissions trading follows directly from comparing the firms' expected costs for both instruments under (I.12)–(I.15). Calculating the differences in the minimal expected social costs from (I.10) for $\beta_{crit} = 0$ (tax only), $\beta_{crit} \to \infty$ (permit trading only) and $\beta_{crit} = \beta^*_{crit}$ directly yields the final two assertions. □

The important point of Proposition 1 is that, for $0 < \delta < 2\hat{\beta}$, the optimal regulation leads to a separating equilibrium, where some firms choose permit trading and some firms choose the tax. Thus firms can be regulated with different instruments according to their technology, even if the regulator does not know which firm uses which technology.

For $\delta \geq 2\,\hat{\beta}$, the optimal policy induces a pooling equilibrium in which all firms choose the tax. In this case, the curvature of the damage function is so small that the increase in expected damage caused by volatile emissions is outweighed by the abatement cost reduction attributable to the higher abatement flexibility that is facilitated by a tax. The condition $\delta < 2\,\hat{\beta}$ arises instead of Weitzman's criterion $\delta < \hat{\beta}$ because, in our setting, firms can be regulated with different instruments. Thus we investigate whether an additional firm should pay the tax or participate in permit trading.[10]

Furthermore, the gain from using the policy menu compared to an optimally chosen single-instrument policy is large if $\hat{\beta}$ and δ are large and if $\delta \approx \hat{\beta}$. Again, this shows that the corresponding result in Mandell (2008) can be generalized to the case of imperfectly correlated cost shocks and a non-uniform distribution of β. If $\delta \approx \hat{\beta}$,

[10]In Weitzman's setting, the question is whether all firms should be regulated with a price or a quantity instrument – comparison of total social costs – whereas we investigate a marginal cost change. Also Proposition 1 shows that the asymmetry between instruments found by Mandell (2008) holds under more general assumptions on firm heterogeneity.

the advantage of a price-based regulation (*abatement cost reduction* due to higher abatement flexibility) and that of a quantity-based regulation (*damage reduction* due to constant aggregate emissions) are closely balanced, as in Weitzman (1974). If, in addition, δ and $\hat{\beta}$ are large, both the abatement cost reduction and the damage reduction are substantial. A mixed instrument, like our approach, is most beneficial in such a situation, as it realizes much of the benefits of both instruments: it provides flexibility to those firms that benefit most from it, and reduces the volatility of aggregate emissions by keeping the aggregate emissions of the other firms constant. In contrast, if a price-based regulation is strongly preferable to a quantity-based one ($\delta \gg \hat{\beta}$), the optimal policy mix induces only few firms to choose permit trading and its advantage compared to a tax is small. Indeed, for $\delta \geq 2\hat{\beta}$, our approach degenerates to a tax. For $\delta \ll \hat{\beta}$, permit trading is strongly preferable to a tax in a single-instrument context, so that the optimal policy mix includes only a small number of tax-paying firms and thus provides only a small benefit compared to pure permit trading.

The optimal policy menu has several interesting characteristics, which we derive in the following corollaries.

Corollary 1. *The tax in the optimal policy menu is the same tax that would be optimal if only an emissions tax were used. Furthermore, the expected permit price equals the tax in the optimal policy menu.*

Proof. Solving the regulator's optimization problem for $\beta_{crit} = 0$ (no permit trading) yields (I.12) as a unique solution. Substituting (I.12)–(I.15) into (I.7) and calculating the expected permit price yields the r.h.s. of (I.12). □

So, the optimal policy menu is comparatively simple. It consists of an emissions tax that should be set as if the tax were the only instrument to be implemented. Then a sufficient number of permits are issued to assure that the expected permit price equals this tax. This result is intuitive. Supplying permits so that the expected permit price equals the tax assures that the expected marginal abatement costs are the same for all firms, regardless of the instrument that they have chosen. This minimizes the total expected abatement costs for a given level of expected emissions. As the expected marginal abatement costs are the same for all firms, the tax (and thus the expected permit price) can be chosen to equalize the expected marginal damage with expected marginal abatement costs, which is a standard requirement for a second-best policy under cost uncertainty.

What remains is to check that all firms voluntarily choose the socially preferred policy instrument. In this way, an optimal allocation of the risk of cost changes and the possibly resulting emissions volatility can be achieved. The remaining policy variables (z_p, z_q^{auc}) can be used to this end. The following corollary provides information on the possible choices of these variables.

Corollary 2. *Define*

$$\omega = \bar{e} - \rho\sigma^2 \frac{\beta^*_{crit}(\hat{\beta}+\delta)}{2(\bar{e}+\alpha\hat{\beta}+\gamma\delta)} - \frac{(2\hat{\beta}-\delta)(\bar{e}-\delta(\alpha-\gamma))}{2(\hat{\beta}+\delta)(1-\mathcal{E}^{\infty}_{\beta^*_{crit}}(1))}. \tag{I.16}$$

a) If $\omega \geq 0$, then for every $z_p \in [0,\omega]$ and for every $z_q^{auc} \in [0,\omega]$, a corresponding $z_q^{auc^*} \in [0,\omega]$ or $z_p^* \in [0,\omega]$ can be found, so that the optimal policy menu specified in Proposition 1 can be implemented.

b) If $\omega < 0$, then the tax exemption has to be negative to implement the optimal policy menu specified in Proposition 1; that is, firms have to pay a fixed fee to switch from permit trading to the emissions tax.

c) The tax exemption is always strictly smaller than the number of freely granted permits per firm.

d) With a non-negative tax exemption, it is never optimal to auction all permits.

Proof. By (I.14), z_q^* is increasing in z_p. Furthermore, by (I.13), $z_q^{auc^*}$ is decreasing in z_q. So, if we want to have $z_p^* \geq 0$, this constraint sets an upper bound for $z_q^{auc^*}$ and the boundary $z_q^{auc^*} \geq 0$ sets an upper bound for z_p^*. Calculating these constraints from (I.13) and (I.14) shows that both equal ω as defined in (I.16). Given the linearity of (I.13) and (I.14), any choice of (z_p, z_q^{auc}) within the interval specified in a) leads to a feasible solution of (I.12)–(I.15) (with $(z_p, z_q^{auc}) \in [0,\omega] \times [0,\omega]$), if $\omega \geq 0$. If $\omega < 0$, then for any $z_q^{auc} \geq 0$, a $z_p < 0$ results from solving (I.12)–(I.15).

Statement c) follows from (I.14), because the second term on the r.h.s. is strictly positive. Statement d) follows from setting $z_p = 0$, which leads to the minimal number of freely granted permits for a non-negative tax exemption. According to (I.14), this minimal number is strictly greater than zero. □

Thus the optimal policy leaves one degree of freedom. Out of the four policy variables $(p_p, z_p, z_q, z_q^{auc})$, only three are needed to achieve the best feasible solution. For each instrument, one policy variable is used to set average emissions $(p_p,\ z_q)$. At least one additional variable (z_p or z_q^{auc}) is necessary to induce the socially desirable self-allocation of the firms to the policy instruments. So, it is possible to have no tax exemption (if $\omega \geq 0$), in which case an appropriate number of permits has to be auctioned. Or all permits can be granted freely, in which case an appropriate tax exemption is necessary. The tax exemption should always be smaller than the number of freely issued permits. Otherwise, the incentive for choosing the tax would be too strong, as firms already profit from the higher flexibility afforded by the tax (compare the last terms in Eq. (I.4) and (I.8)). Indeed, it might be necessary to actively discourage firms from choosing the tax by using a negative tax exemption (a fixed fee for not participating in permit trading). This can happen if the firms strongly favor the greater flexibility afforded by the tax (large $\hat{\beta}$) or if, from a social perspective, nearly all firms should participate in permit trading due to a strongly convex damage function (small δ).

A further interesting question is how the switch from a conventional regulation to the optimal policy menu affects the firms: Will such a switch increase the costs of some firms so that they are likely to oppose the policy change, or will all firms gain? If we do not consider auctioning permits and if we compare our policy menu with a conventional permit market with the same number of permits per firm, the answer is trivial. All firms can choose the same regulation, and thus no firm can lose by having the option to choose a different regulation. The same holds for comparing our approach with an emissions tax that equals Eq. (I.12).

However, if we compare an optimally designed permit market with our optimal policy menu, a different answer might be possible, because if some firms choose the tax, the aggregate marginal abatement costs of the permit-trading firms change and thus the optimal number of permits per firm is altered. The following corollary shows that this does not affect the firms negatively.

Corollary 3. *Compared to an optimally designed permit market with freely granted permits, the optimal policy menu characterized in Proposition 1 (without auctioned permits) leads to smaller expected costs for every firm.*

Proof. Calculating the reduction in expected costs for a permit-trading firm yields

$$\frac{\left(\bar{e}+\alpha\hat{\beta}+\gamma\delta\right)\left(\bar{e}-(\alpha-\gamma)\delta\right)\left(\delta-2\hat{\beta}\mathcal{E}^{\infty}_{\beta^*_{crit}}(1)\right)}{2(\hat{\beta}+\delta)^2\left(1-\mathcal{E}^{\infty}_{\beta^*_{crit}}(1)\right)}. \tag{I.17}$$

For a firm that chooses to pay the tax, we get a cost reduction of

$$\frac{\left(\delta - 2\hat{\beta}\mathcal{E}^{\infty}_{\beta^*_{crit}}(1)\right)\left(\bar{e} + \alpha\hat{\beta} + \gamma\delta\right)(\bar{e} - (\alpha - \gamma)\delta) + (\beta - \beta_{crit})(\hat{\beta} + \delta)^2\rho\sigma^2}{2(\hat{\beta} + \delta)^2\left(1 - \mathcal{E}^{\infty}_{\beta^*_{crit}}(1)\right)}. \tag{I.18}$$

Since by construction $\mathcal{E}^{\infty}_{\beta^*_{crit}}(1) \leq \mathcal{E}^{\infty}_{\beta^*_{crit}}(\beta)/\hat{\beta}$ and, by Prop. 1, $\mathcal{E}^{\infty}_{\beta^*_{crit}}(\beta) = \delta/2$, (I.17) is non-negative. By Proposition 1, only firms with $\beta \geq \beta_{crit}$ choose the tax, so that (I.18) is also non-negative. □

So, the introduction of the policy menu results in a gain for all firms compared to an optimally designed single-instrument policy.[11] As the firms' preferences with regard to the instrument choice stand in marked contrast to the social planner's preferences, this raises the question of whether the reliance on self-selection is costly from a social perspective. Could lower expected social costs be attained if the firms could be assigned to the instruments depending on their technologies? The following proposition shows that the answer is negative: Even a fully-informed assignment of firms to instruments cannot improve on self-selection.

Proposition 2. *In terms of expected social costs, there is no allocation of firms to instruments that could improve on the optimal policy menu characterized in Proposition 1.*

Proof. If the social planner could arbitrarily assign firms to the tax and to permit trading, she could set the slope of the aggregate marginal abatement costs[12] of the firms paying the tax and that of the firms participating in permit trading. Let n_p denote the fraction of firms assigned to the tax; let β_p be their average technology; denote the average technology of the permit-trading firms by β_q; and their fraction by n_q. Consistency with the prevalence of the different technologies demands that $n_p + n_q = 1$ and that $n_p\beta_p + n_q\beta_q = \hat{\beta}$. Let p_p denote the tax and z_q denote the number of permits per firm. As the tax exemption and the auctioning of permits have no allocative consequences in this setup, we neglect these.

Calculating the aggregated expected abatement costs of the firms assigned to the tax yields $C_p = n_p\beta_p(p_q^2 - \alpha^2 - \sigma^2)/2$. Those of the permit-trading firms are $C_q =$

[11] It is also true that all firms are at least as well off in our approach as with the assignment used in Mandell (2008), if no permits are auctioned (each firm could select the instrument in our context to which it is assigned there but may choose not to do so).

[12] Only this aggregate information is relevant from the perspective of the social planner (Roberts and Spence, 1976).

$(n_q/(2\beta_q))((\bar{e}-z_q)(\bar{e}-z_q+2\alpha\beta_q)-\beta_q^2(1-\rho)\sigma^2)$. The expected damage is $(((\bar{e}-\beta_p(p_p-\alpha))n_p+n_q z_q)((\bar{e}-\beta_p(p_p-\alpha))n_p+n_q z_q+2\gamma\delta)+n_p^2\rho\sigma^2\beta_p^2)/(2\delta)$. Minimizing the sum of these terms yields the tax (I.12), a number of permits z_q for which the expected permit price equals this tax, as well as $n_p\beta_p=\delta/2$, for $\delta<2\hat{\beta}$, and $n_p\beta_p=\hat{\beta}$, otherwise, which corresponds to (I.15). This assignment leads to the same expected social costs as the optimal policy menu. □

Proposition 2 is noteworthy in that it shows that the self-selection mechanism suffices to eliminate all welfare losses attributable to the regulator's lack of information with regard to the firms' technologies. Compared to Mandell (2008) there is an additional constraint (asymmetric information) and an additional policy variable (tax exemption/auctioned permits). Owing to the self-selection mechanism, this additional policy variable suffices to overcome the additional constraint, so that the same expected social costs can be attained as in Mandell (2008).

This is somewhat surprising, given that the sorting under self-selection differs from the intuition in Weitzman (1974). Firms with a flexible technology, and thus highly volatile emissions, choose the tax, where the emissions volatility leads to higher expected damage. But only the slopes of the aggregate marginal abatement costs of the two groups of firms (tax, permit trading) matter. These can be controlled with the self-selection mechanism, because it induces a predictable instrument choice of the firms and has the ability to control the size of each group. Indeed, compared to a sorting based on the intuition of Weitzman (1974), where firms with a flexible technology are assigned to permit trading, our approach leads to fewer tax-paying firms.[13] This corresponds to the relationship between the sorting of firms to instruments and the size of each group of firms discussed in Mandell (2008).

An interesting question is whether enlarging the policy menu, either by introducing a standard or by using several permit markets or several tax schemes, would yield even better results. Proposition 2 implies that the answer is negative. Price- and quantity-based policies differ only with regard to two effects (Weitzman, 1974): The increase in environmental damage due to volatile emissions in a price-based regulation, and the increase in the firms' expected costs due to the reduced adjustment options in a quantity-based regulation. The relative importance of these effects de-

[13] Such an assignment would sort all firms with $\beta<\beta_{crit}$ to the tax and the optimal β_{crit} would be characterized by $\mathcal{E}_0^{\beta_{crit}}(\beta)=\delta/2$ (for $\delta<2\hat{\beta}$) instead of (I.15). So, by the definitions of $\mathcal{E}_0^{\beta_{crit}}(\beta)$ and $\mathcal{E}_{\beta_{crit}}^{\infty}(\beta)$, the fraction of firms that choose the tax is smaller in our setup whenever $\delta<2\hat{\beta}$, that is, whenever there is a permit market. As can be easily calculated, the resulting marginal abatement costs are identical in both policy settings for both subgroups of firms.

pends monotonically on the difference between the curvature of the aggregate cost and that of the aggregate damage function. This implies that there is at most a single value for the curvature of the aggregate abatement costs at which the preferability of price-based and quantity-based policies changes. Therefore, a combination of one price-based and one quantity-based instrument suffices.[14] Introducing a standard as a third policy instrument is also not welfare increasing, because a standard is dominated in terms of social costs by permit trading.

As a final result we briefly show that our assumption that the firms differ only with regard to β but not with regard to α is innocuous.

Corollary 4. *Whenever the expected permit price equals the tax, heterogeneity with regard to the parameter α does not influence a firm's choice between the emissions tax and permit trading.*

Proof. The expected costs of a firm that pays the tax are not influenced by heterogeneity with regard to α, so that (I.4) remains unchanged. But if the firm chooses permit trading, its expected costs are changed by the cost heterogeneity, because the equilibrium price for permits depends on the cost functions of all firms participating in the permit market. However, (I.7) is linear in α, so that α can be replaced in this equation by the average value of this parameter among all firms that participate in permit trading. Calculating the resulting expected costs and equating them with (I.4) to identify the indifferent firm yields a condition that is independent of the firm's α whenever the expected permit price equals the emissions tax. □

If there is additional heterogeneity with regard to the intercept of the marginal abatement cost functions, this does not affect the self-selection mechanism. From a firm's perspective, the preferability of an instrument does not depend on the firm's value of α if the expected permit price equals the emissions tax, which is necessary for the policy menu to be optimal. Therefore, the firms still choose their instrument according to their cost parameter β. This is socially optimal, because α is irrelevant for the social preferability of price or quantity instruments (Weitzman, 1974).

Our analysis has shown that the self-selection approach can be socially beneficial in that it reduces the social costs of informational constraints. A different approach to

[14]In contrast, with a hybrid regulation, it is optimal to use an infinite number of instruments (Roberts and Spence, 1976). The difference is that, in the hybrid regulation, the realization of the cost shocks determines which instrument is actually used. Thus the policy needs to provide for an infinite number of possible states of nature. In our approach, the instruments differ between firms, and, as argued above, it suffices to partition firms in two groups.

the same end is the hybrid regulatory scheme of Roberts and Spence (1976). There, firms can decide after they have observed their actual costs whether to pay a fixed carbon tax, to receive a subsidy, or to participate in permit trading. The difference is whether firms choose ex-ante or ex-post. In our regulatory approach (where firms choose ex-ante), the firms' decisions are based solely on their production technology. In contrast, with ex-post instrument choices, as in Roberts and Spence (1976), the firms' decisions are based solely on the realization of the cost uncertainty with all firms choosing the same instrument.

To compare the relative merits of these two concepts, two effects have to be taken into account. First, a hybrid instrument has the advantage of being cost effective; all firms are regulated with the same instrument and their marginal abatement costs are identical. In our approach, the realization of the permit price will almost surely deviate from the emissions tax, so that tax-regulated firms and permit-trading firms will have different marginal abatement costs, resulting in higher total abatement costs. Second, both instruments reduce the costs of uncertainty by implementing a price/quantity relationship of emissions that is closer to the marginal damage than the constant quantity set by a conventional permit market (reduced volume error). However, the instruments differ substantially with regard to this price/quantity relationship.

A hybrid instrument implements a step-function consisting of an upper and a lower price boundary and a fixed quantity in between. In contrast, our approach has a number of firms whose aggregate emissions are constant (permit-trading firms) and a number of firms whose aggregate emissions varies with the realization of the cost uncertainty. For the case with perfect correlation of the cost uncertainty (as in Roberts and Spence (1976)), the relationship between the permit price[15] and total emissions can be calculated as $p^q = \hat{p} + 2\ dE/\delta$, where $\hat{p}$ denotes the expected permit price and where dE is the deviation of total emissions from their expected value. Thus our approach implements a price/quantity relationship that is linear but steeper than the marginal damage function.[16] Figure 3 depicts this relationship

[15]As we have two groups of firms with differing marginal abatement costs, it is not possible to define "the" marginal abatement costs that can be related to total emissions. Relating the permit price to total emissions is useful to illustrate the difference between the two approaches.

[16]A price/quantity relationship that corresponds to the marginal damage function is feasible but not optimal. This is a consequence of the inefficiency induced by using two instruments simultaneously. A relationship between the permit price and total emissions that equals the marginal damage (and thus has the smaller slope $(1/\delta)$) would result in an ex-post efficient regulation of the permit-trading firms; their marginal abatement costs would always equal the marginal damage. This does not hold for tax-paying firms, which face the constant price p_p. To implement the slope $1/\delta$, many firms would have to choose the tax, as only the aggregate emissions of tax-paying firms

and that induced by a hybrid regulation.

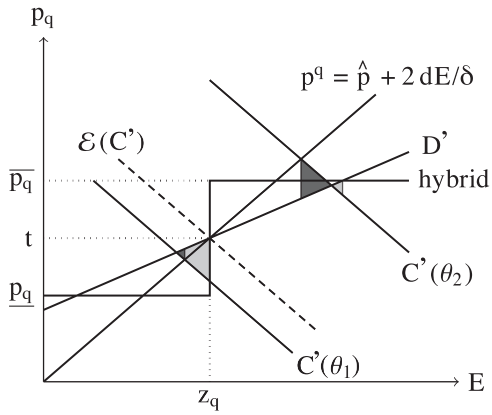

Figure I.3: Policy à la carte vs. hybrid regulation. Welfare losses in the permit market under the policy menu (black areas) and under a hybrid regulation (grey areas) for a small (θ_1) and a large (θ_2) cost shock. The additional welfare loss due to the permit price not equaling the emissions tax is not depicted.

As this figure shows, the price/quantity relationship of our approach is closer to the marginal damage for small shocks but further away for larger shocks. Thus it can be expected that our approach works better than a hybrid regulation in most cases with small levels of uncertainty, but that a hybrid regulation is preferable for cases of high uncertainty. Of course, a hybrid regulation will use price limits that are closer to the expected price if the uncertainty is small than if it is large. However, it faces the problem that emissions (and thus the damage) increase strongly with a cost shock, once the upper price limit is binding. It thus has to balance this excess-damage caused by a low price-ceiling with the cost reduction achieved by being close to the marginal damage for small shocks. Therefore, it cannot reduce the volume error as strongly as our approach for small levels of uncertainty.

Furthermore, the more heterogeneous firms are, the more beneficial it becomes to have different instruments for different firms instead of different instruments for different realizations of the cost shocks. Thus we expect that, in most cases, our approach will be preferable to a hybrid regulation if there is substantial firm heterogeneity. Figure 4 supports both of our conjectures for a numerical example.[17]

are variable. Thus we would have better regulated permit-trading firms but fewer of them, which is not optimal.

[17]The example assumes that β and θ are uniformly distributed with $\beta \in [\hat{\beta} - \Delta, \hat{\beta} + \Delta]$, and that $\bar{e} = 1$, $\alpha = 2$, $\gamma = 2$, $\widehat{\beta} = 3$, $\rho = 1$, and $\delta = 3$.

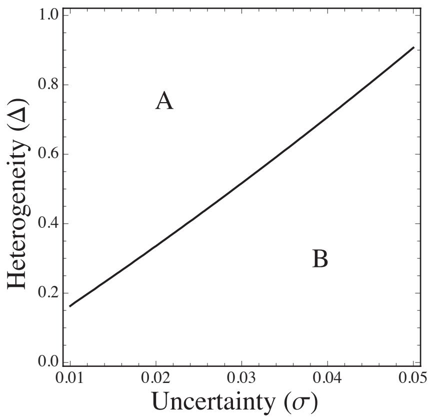

Figure I.4: Comparison of our approach with an optimally designed hybrid regulation in a numerical example; the policy menu is preferable in region A, the hybrid regulation in region B.

I.5 Conclusions

In this paper, we have analyzed an environmental policy in which regulated firms are offered a policy menu that allows them to choose between two different instruments. The objective of this approach is to overcome informational asymmetry with regard to firms' technologies in much the same way that contract-based screening devices do, for example, in labor or insurance markets. We have shown that, under uncertainty and asymmetric information, using such a policy menu reduces expected social costs compared to a single instrument. With an optimized policy menu, every firm chooses the instrument that is best from a social perspective. In this way, the asymmetric information problem can be overcome and the welfare losses caused by uncertainty can be reduced. Indeed, the second-best solution without asymmetric information derived in Mandell (2008) can be attained. Finally, the optimal policy menu is comparatively simple and thus provides an applicable solution to the problems posed by information constraints in environmental policy.

Our investigation was inspired by the climate policy implemented in Switzerland, where firms can choose between an emissions tax and permit trading. There are two main differences between our model and this policy. The first difference is that the firms that have chosen to participate in emissions trading can rescind their choice at the end of a five-year trading period. But this is unlikely to matter, as firms will probably become locked into their instrument choice (since a firm's choice of a technology depends on whether the firm is regulated with a price- or a quantity-based instrument (Krysiak, 2008b)). If investments involve sunk costs, a change from one instrument to another is unlikely to occur, because a firm would either have to use a technology that is suboptimal for the new instrument or it would have to invest anew.

The second difference is that the tax exemption offered to firms depends on the firms' labor costs. Our results suggest that this is suboptimal, because a self-selection based solely on abatement flexibility would be optimal. Furthermore, the incentive for choosing the tax seems to be too small; a large fraction of firms have opted for permit trading. Given that the costs of emissions volatility is small for greenhouse gases due to their long retention period in the atmosphere, this seems to be suboptimal (Newell and Pizer, 2003). Thus the general approach used in Switzerland is reasonable but the policy is suboptimally designed.

Altogether, our analysis shows that it is socially beneficial to let firms choose their regulation. It has long been accepted that it is more efficient to regulate abatement activities by using a tax or a permit price than by using a command-and-control policy, since firms are typically better informed about the costs of their abatement activities than a regulator. Our results suggest that this idea can be taken a step further: Under uncertainty and asymmetric information, it is better to let firms choose the instrument with which they are regulated than if this decision is made by a governmental agency.

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Essay II

Prices vs. Quantities: An Empirical Study of Firms' Instrument Choices[1]

Iris Maria Oberauner

University of Basel, Faculty of Business and Economics, Department of Environmental Economics, Peter Merian-Weg 6, 4002 Basel, Switzerland, *Iris.Oberauner@unibas.ch*

Abstract

A long-standing theoretical discussion on the relative merits of prices vs. quantities for regulating emissions under uncertainty exists in the environmental policy literature. However, empirical evidence with regard to instrument choice has not been put forward so far. In particular, very little is known about instrument preferences from the perspective of firms. Based on Swiss firm data, we address this issue by empirically investigating a policy where firms can self-select between a tax (with a wage-based tax exemption) and emissions trading (with a grandfathering mode of permit allocation). Specific theory on Swiss policy design identifies the influential factors for instrument choice as being permit allocation, wages, uncertainty in abatement costs and the flexibility of firms' abatement technologies. We confirm evidence for the first two factors, but were unable to find evidence for the latter ones. Moreover, high-abatement firms prefer permit trading.

Keywords: Prices vs. Quantities, Instrument Choice, Swiss Climate Policy, Environmental Policy à la Carte

JEL classification: Q58, Q54, D81, D82

[1]Submitted to *Environmental and Resource Economics*. Invited for revision and resubmission January 2012.

II.1 Introduction

It is widely accepted by environmental economists that market-based instruments – like a tax or permit trading – are the preferred policy to reduce harmful emissions in efficiency terms. If firms face uncertainty in the costs of abating these emissions, then even the choice between a price and a quantity instrument matters. In this context, there is extensive theoretical literature on the relative merits of the instruments: a tax vs. permit trading vs. mixed policies.[2] If, in addition to uncertainty, asymmetric information between the regulatory authority and the firms with regard to their used abatement technologies deteriorates the outcome, then theory suggests a "Policy à la Carte", i.e. a self-selection mechanism with the instrument choice being delegated to firms (Krysiak and Oberauner, 2010). In contrast to the theory, empirical studies on these issues are rare. Only little is known on the relative performance of prices vs. quantities in their effective use. This shortcoming in the empirical literature applies in particular to the analysis of the instrument preferences from the perspective of firms.

In the present paper, we redress the lack of evidence by empirically investigating the instrument preferences of firms when the regulatory authority allows them to self-select between a tax and permit trading. We have chosen the self-selection mechanism that is implemented in Switzerland as providing optimal data for our empirical research on instrument choice from the perspective of firms. The Swiss Confederation offers firms a policy menu to regulate carbon dioxide (CO_2) emissions from which firms can choose their preferred instrument. The policy menu consists of a tax (charged on every ton of CO_2) and permit trading (with free-of-charge permit allocation). The revenue of tax payments is refunded to taxpaying firms proportional to their gross wages.

This unique policy offers a challenging spectrum of empirical research associated with the prices-versus-quantities debate. On the one hand, the performance of different policy regimes can be analyzed under equal economic conditions. Moreover, it offers valuable information on the incentives that this policy menu offers firms when choosing between the tax and permit trading. The main focus of our paper concerns the latter field of research. We empirically investigate firms' instrument

[2]See for example Williams (2002) and Adar and Griffin (1976) for instrument choice between a tax and permit trading, Hepburn (2006) for a review on the choice between a tax, permit trading and a hybrid instrument (as proposed by Roberts and Spence, 1976), and Mandell (2008) for the simultaneous use of a tax and permit trading compared to a single instrument policy.

preferences thereby providing valuable insights on compliance costs associated with specific attributes of firms that can be applied to future environmental policy design and implementation.

Our approach for the empirical analysis of firms' instrument preferences is the following. Based on the theoretical model of self-selection in environmental regulation provided by Krysiak and Oberauner (2010), a formal decision criterion on firms' instrument choices is derived that features the specific attributes of Swiss climate policy design. Based on this criterion, an empirical model is constructed that is tested for Swiss firm data.

Theory predicts firms' instrument preferences for emissions trading whenever the expected value of the permit allocation net of trade-specific fixed costs outweighs the expected net benefits of paying the tax (i.e. the expected tax refund plus a flexibility-uncertainty advantage under a tax net of tax-specific fixed costs). Our results gained from a logit regression confirm the evidence regarding permit allocation and the tax refund. We were unable, however, to find evidence that firms' exposure to uncertainty and their flexibility in abatement technologies influences firms' instrument preferences. Moreover, contrary to theoretical predictions, our results revealed that high-abatement firms tend to choose emissions trading.

The paper is organized as follows. In the next section, we briefly review the existing literature on the choice between prices and quantities in this context. Section II.3 introduces Swiss climate policy. In Section II.4, the theoretical model is presented and the criterion for firms' decisions between the tax and permit trading is formally derived. Data and variables for our empirical analysis are sketched in Section II.5. In Section II.6, the empirical results with respect to firms' instrument preferences are presented and discussed. Finally, we conclude in Section II.7.

II.2 Related Literature

The main theoretical foundation for our analysis originates from the prices-vs.-quantities discussion in the environmental policy literature. While a price and a quantity instrument perform equally under complete information, the instrument choice becomes critical if there is uncertainty with regard to firms' abatement costs.

In his seminal paper "Prices vs. Quantities", Weitzman (1974) has shown that from a social perspective firms should be regulated by a tax whenever the value of the slope of the marginal abatement cost function outweighs the value of the slope of the marginal damage function in absolute terms, and uncertainty renders a first-best outcome impossible. A quantity instrument – and more precisely a standard – is preferable when the opposite is true. Yet, Weitzman's findings are still valid when the tax is compared with a quantity instrument designed to be a scheme of tradable permits, as shown by Williams (2002).

The choice of instrument to be implemented has gained particular attention in the context of climate change mitigation. Contributors to the discussion on instrument choice for countering greenhouse gas (GHG) emissions and stock pollutants in general are – among others – Hoel and Karp (2002), Pizer (2002), Newell and Pizer (2003), and Nordhaus (2007). Due to the uncertainties inherent in the regulation of GHG emissions, the authors emphasize the relative merits of a tax. First and foremost and in line with Weitzman (1974), they argue that flat marginal damages of GHGs make the tax superior in efficiency terms to emissions trading. In contrast, by adding enforceability considerations to the analysis under uncertainty, Rohling and Ohndorf (2010) argue in support of a quantity instrument in the context of international climate-related policies. Enforcement concerns in their paper, however, are only an issue in the international context of national sovereignty.

Roberts and Spence (1976) were the first to introduce the concept of a hybrid instrument. They propose a scheme of tradeable permits with a price ceiling and a price floor for permits (i.e. a tax and a subsidy) with an ex-post choice of instrument depending on how the uncertainty is resolved. Their approach results in a single instrument regime with all firms regulated by one of the three instruments. Pizer (2002) shows that a hybrid system with a "safety valve" is a good alternative to the tax in the regulation of greenhouse gases.

All these approaches on instrument choice in environmental regulation have one thing in common: The authors all refer to a single instrument policy, i.e. when the whole industry or market is regulated with one instrument. Mandell (2008), by contrast, analyzes a policy design in which the market is separated into two groups of firms that are regulated by different instruments simultaneously: One group of the firms is regulated using a tax, the other group is regulated using permit trading. Compared to a single instrument policy, an emissions level can be achieved that more closely approximates to the efficient one, thereby reducing the welfare loss due to uncertainty. To optimally assign the firms to the instruments, the regulatory authority needs information on the technologies used by firms to abate emissions, i.e. on their abatement cost structure. Firms do not have an incentive, however, to reveal these costs. Thus, it is reasonable to assume the abatement technologies used by firms will be private knowledge.

In their Policy-à-la-Carte approach, Krysiak and Oberauner (2010) take this asymmetric information problem between the regulator and the firms into account by letting the better informed agents (firms) choose the instrument. In their approach, the regulator offers firms a policy menu that consists of a tax and permit trading, between which firms can self-select. Accompanied by a tax exemption and/or partly auctioned permits, the policy menu provides appropriate incentives for firms to make an instrument choice that is socially optimal. Thus, the same expected social costs can be achieved as in Mandell (2008) and the asymmetric information problem can be overcome.

To our knowledge – besides Krysiak and Oberauner (2010) – only one paper exists that explores the selection of choices available to firms for regulating pollution emissions. Delmas and Marcus (2004) discuss the firms' preferences between a command-and-control (CAC) instrument and negotiated agreements based on the transaction costs incurred by those instruments. However, the authors derive neither cost-minimizing analytical nor empirical criteria for instrument choice. Moreover, their focus is on transaction costs, and not on the costs that accrue from abatement and regulation, which are, however, the main drivers of firms' decision-making behavior.

II.3 Swiss Climate Policy Design

Active measures to combat climate change were implemented in Switzerland in January 2008. The Swiss Confederation charges a tax on CO_2 emissions from the combustion of fossil fuels used in generating heat, cooling or electricity.[3] However, firms can gain exemption from this tax when they commit to a legally-binding reduction in their CO_2 emissions at a predetermined level.

Concerning large emitters, the commitment to this quantity target automatically leads to participation in the national emissions trading scheme with free permit allocation (corresponding to their quantity target) and unrestricted trade in their allowances. In contrast, small- and medium-sized emitters are discriminated against by this policy. Their quantity alternative can best be portrayed as a performance-

[3] Carbon dioxide emissions from transport are regulated separately.

based standard with a permit-purchase option.[4] So, if firms were buyers of permits, they can be treated as if they were fully involved in emissions trading. Potential sellers, however, are ruled out from any trade. According to this policy design, firms explicitly have the choice of being regulated either by a price (the CO_2 tax) or by a quantity instrument (permit trading or standard with a permit-purchase option). For the time being, we pass over the discrimination of small- and medium-sized firms and treat all firms as if they were unrestricted in their choice between the tax and permit trading. We will examine this aspect more thoroughly in Section II.6 and in Appendix II.A.3.

Specific design elements for both instruments are legally documented in the CO_2 Act, passed by the Swiss parliament in 1999 (Swiss Federal Assembly, 1999). Firms that opted for the tax paid 12 Swiss francs on every ton of CO_2 emitted in 2008. The tax rate follows a phasing-in process that is conditional on annual national reduction achievements.[5] Tax revenues are refunded to taxpaying firms proportional to their gross wages. According to the Swiss Federal Office for the Environment (2010c), the tax refund rate in 2008 is approximately 37 Swiss francs per 100,000 Swiss francs gross wages.

The national emissions trading scheme is operated in a cap-and-trade style. The permit allocation method used is grandfathering[6], i.e. free permit allocation based on historic emissions, with the emission allowances referred to as Swiss Units (CHUs). The overall cap is determined by the sum of individual emission targets of firms that are allotted with permits.

[4]The Energy Agency for the Economy (EnAW) serves as an intermediator between the Swiss Confederation and firms. It provides three quantitative commitment models for firms: (1) Energy Model for large energy-intensive firms, (2) SME Model, and (3) Benchmark Model, both for small- and medium-sized emitters. Firms in the latter models do not receive free permits when they commit to a quantity target, but are permitted to buy emission allowances on the permit market to cover emissions in excess of their individual targets (Swiss Federal Office for the Environment, 2010a). Thus, Swiss climate policy design discriminates against small- and medium-sized tax-exempted, low-abatement-cost firms by depriving them of incentives to abate beyond their reduction target.

[5] While the tax rate was not increased in 2009, it was raised to 36 Swiss francs in 2010, as the national emission reduction target was not met in 2008.

[6]According to the CO_2 Act (Swiss Federal Assembly, 1999), the determination of firms' individual reduction targets is based on their historic abatement measures, the costs of abatement measures, their international competitive position, and their expected output growth. The correlation coefficients between historic emissions (2006 and 2007) and permit allocation in 2008 amount to 0.9919 and 0.9915, respectively. Thus, it is reasonable to assume a pure grandfathering mode of permit allocation.

II.4 Theoretical Model

Swiss climate policy design and timing is very similar to the Policy-à-la-Carte model provided by Krysiak and Oberauner (2010). So, we adopt their theoretical model, adjust it for specific elements of the Swiss policy, and derive a formal decision criterion on firms' choices between a tax and permit trading.

In their model, Krysiak and Oberauner (2010) assume a continuum of firms with mass one that emit a homogeneous and uniformly mixed pollutant. To reduce environmental damage from emissions, the regulator offers firms a policy menu that consists of a tax and permit trading, from which firms choose their preferred instrument for several periods (self-selection mechanism). There is uncertainty in abatement costs that only resolves when the abatement decision has to be made. Besides, the technologies used to abate emissions differs among firms and is private knowledge. In their approach, Krysiak and Oberauner (2010) allow for two additional "fine-tuning" variables (tax exemption modeled as a lump sum and partly auctioned permits) that ensure a self-allocation of firms to instruments that is socially optimal.

This approach is adjusted to specific elements of Swiss climate policy design. First, the tax exemption is modeled as a refund of tax revenues for taxpaying firms based on their wages. Second, the allocation of permits is entirely free of charge and based on (unregulated) historic emissions, i.e. grandfathering. Finally, we allow for instrument-specific fixed costs that are supposed to differ substantially between the tax and permit trading within the Swiss policy.[7]

From the policy menu, firms will prefer the instrument for which lower compliance costs (abatement costs plus regulation costs) are to be expected. The decision criterion for a firm's choice is, thus, derived by the difference in the expected costs under the instruments. Another way of thinking than in terms of abatement costs, is that firms make their decision based on expected savings from emitting the pollutant net of regulation costs. Using this "inverse" model makes the exposition – especially with respect to the empirical model – more intuitive.

Accordingly, if a firm opts for the tax t, it will choose an emissions level e that

[7]We expect the fixed costs to be low or even zero for the tax, but substantial for permit trading. For trading firms, these costs comprise the efforts to receive exemption from the tax, the EnAW membership fee, consulting costs, monitoring, reporting and verification etc. Oberauner and Krysiak (2010) specify the costs incurred under both regimes as well as the effects of the instruments on several cost categories from the perspective of firms.

maximizes the net savings function[8]

$$\max_{e\geq 0} \quad S_t(e) = (\alpha + \theta)e - \frac{e^2}{2\beta} - te + \tau w - F_t, \tag{II.1}$$

with θ being the stochastic parameter in the savings, τ the refund rate of tax revenues, w the firm's gross wages, and F_t the fixed costs incurred with the tax. Furthermore, the firm's technology is characterized by the parameters $\alpha \geq 0$ and $\beta > 0$. Eq. (II.1) characterizes the firm's savings from emitting a pollutant, minus the tax payment, plus the refund share of tax revenues that is conditional on the firm's wages, and minus the tax-specific fixed costs.

Uncertainty is modeled by the parameter θ that is firm-specific, but correlated among firms with $\rho \in (0, 1]$. θ has an expected value of zero and a positive variance of σ^2.

Firms are heterogeneous in two dimensions: They differ in their technology parameter β and in their wages w.[9] Let the joint density of β and w be $f(w, \beta)$. From Krysiak and Oberauner (2010), we know that firms with a flexible technology (high β) prefer the tax, whereas firms with a low β prefer permit trading. The intuition for this self-allocation to instruments is the following. In expected net savings terms, firms benefit from uncertainty as they can adjust their emissions to shocks. This effect is stronger under the tax, as the correlation between firms' savings and the permit price reduces the adjustment possibilities of trading firms.[10] Furthermore, the more flexible firms are in their abatement technologies (high β), the larger their benefit from uncertainty. Consequently, more flexible firms gain most under the tax.

Firms that are indifferent between the instruments due to expected net savings equality are denoted by the technology parameter $\beta_{crit}(w)$ which is, in turn, conditional on wages. Hence, all firms with a combination of (w, β) such that $\beta \in [0, \beta_{crit}(w))$ will participate in permit trading. Otherwise, i.e. if $\beta \in [\beta_{crit}(w), \infty)$, firms will pay the tax. Furthermore, we assume $f(w, 0) = 0$, $f(0, \beta) = 0$, $\lim_{w\to\infty} f(w, \beta) = 0$ and $\lim_{\beta\to\infty} f(w, \beta) = 0$.

Solving the first-order condition of (II.1) results in optimal emissions

$$e_t^* = \beta(\alpha + \theta - t). \tag{II.2}$$

[8] Subscript t indicates the tax.

[9] As shown by Krysiak and Oberauner (2010), heterogeneity with regard to α has no effect on the results and is therefore assumed to be constant across firms.

[10] Ex-post, the permit price is determined by abatement cost realization, whereas the tax rate is constant no matter how θ realizes.

The refund rate τ is endogenously determined as the ratio of tax revenues to the aggregate of gross wages of taxpaying firms. Given firms' self-allocation to instruments as proposed by Krysiak and Oberauner (2010), τ is

$$\tau = \frac{\theta_E\, t + t\,(\alpha - t)\displaystyle\int_0^\infty\!\!\int_{\beta_{crit}(w)}^\infty \beta f(w,\beta)\, d\beta\, dw}{\displaystyle\int_0^\infty\!\!\int_{\beta_{crit}(w)}^\infty w f(w,\beta)\, d\beta\, dw}, \tag{II.3}$$

with $\theta_E = \int_0^\infty\int_{\beta_{crit}(w)}^\infty \beta\theta f(w,\beta)\, d\beta\, dw$ and $\mathcal{E}\left(\theta_E\right) = 0$.

By substituting Eq. (II.2) and (II.3) into Eq. (II.1) and taking expectations, we get expected net savings of

$$\mathcal{E}\left(S_t(e_t^*)\right) = \frac{\beta}{2}(t^2+\alpha^2) - \alpha\beta t + wt\,(\alpha - t)\,\frac{\displaystyle\int_0^\infty\!\!\int_{\beta_{crit}(w)}^\infty \beta f(w,\beta)\, d\beta\, dw}{\displaystyle\int_0^\infty\!\!\int_{\beta_{crit}(w)}^\infty w f(w,\beta)\, d\beta\, dw} + \frac{\beta}{2}\sigma^2 - F_t. \tag{II.4}$$

Analogously, if a firm chooses to participate in permit trading, it maximizes the function[11]

$$\max_{e\geq 0} \quad S_p(e) = (\alpha+\theta)e - \frac{e^2}{2\beta} + p(\psi\bar{e} - e) - F_p, \tag{II.5}$$

where p denotes the price of permits, ψ the allocation rate of permits to historic emissions $\bar{e}$, and F_p the fixed costs. The price term in Eq. (II.5) is positive when the firm is a seller of permits, and negative when the firm holds a buyer position. The optimal level of emissions of a firm participating in emissions trading is then

$$e_p^* = \beta(\alpha + \theta - p). \tag{II.6}$$

The price of permits is endogenously determined, as it depends on the number of firms that choose permit trading. Calculating the market-clearing price of permits gives

$$p = \alpha - \psi\bar{e}\,\frac{\displaystyle\int_0^\infty\!\!\int_{\beta_{crit}(w)}^\infty f(w,\beta)\, d\beta\, dw}{\displaystyle\int_0^\infty\!\!\int_{\beta_{crit}(w)}^\infty \beta f(w,\beta)\, d\beta\, dw} + \theta_p, \tag{II.7}$$

[11] Subscript p indicates permits.

with $\theta_p = \int_0^\infty \int_{\beta_{crit}(w)}^\infty \theta\beta f(w,\beta)\,d\beta\,dw / \int_0^\infty \int_{\beta_{crit}(w)}^\infty \beta f(w,\beta)\,d\beta\,dw$, reflecting the price uncertainty due to uncertainty in firms' savings. Furthermore, we have $\mathcal{E}\left(\theta_p\right) = 0$, $\mathcal{E}\left(\theta\theta_p\right) = \rho\sigma^2$ and $\mathcal{E}\left(\theta_p^2\right) = \rho\sigma^2$.

As shown by Krysiak and Oberauner (2010), for a policy menu design to be optimal, the expected price of permits has to equal the tax rate. Then, expected marginal savings among all firms are equalized, and firms' net savings are at a maximum. Thus, when choosing an instrument from the policy menu, a firm anticipates an optimal policy, i.e. $\mathcal{E}\left(p\right) = t$.

With a permit price as in Eq. (II.7), optimal emissions as in Eq. (II.6), and taking into account that $\mathcal{E}\left(p\right) = t$, the expected net savings are

$$\mathcal{E}\left(S_p(e_p^*)\right) = \frac{\beta}{2}(t^2+\alpha^2) - \alpha\beta t + \psi\bar{e}t + \frac{\beta}{2}(1-\rho)\sigma^2 - F_p. \tag{II.8}$$

Given the expected net savings under both instruments, the decision criterion for a firm's choice of instrument is formulated as

$$\begin{aligned}\Delta =& \mathcal{E}\left(S_p(e^*)\right) - \mathcal{E}\left(S_t(e^*)\right) = \\ &= \left(\psi\bar{e}t - F_p\right) - \left(wt\left(\alpha - t\right) \frac{\displaystyle\int_0^\infty \int_{\beta_{crit}(w)}^\infty \beta f(w,\beta)\,d\beta\,dw}{\displaystyle\int_0^\infty \int_{\beta_{crit}(w)}^\infty w f(w,\beta)\,d\beta\,dw} + \frac{\beta}{2}\rho\sigma^2 - F_t \right).\end{aligned} \tag{II.9}$$

Hence, a firm chooses to participate in emissions trading whenever the expected benefits of trading (first brackets of Eq. (II.9)) outweigh the expected benefits under the tax (second brackets of Eq. (II.9)). Otherwise, the firm chooses to pay the tax, i.e. when Δ is negative. The benefits of permit trading are characterized by the value of permits allotted to a firm minus the trade-specific fixed costs. By contrast, the benefits of the tax comprise the refund of tax receipts (first term), plus the flexibility advantage under uncertainty for a taxpaying firm that results from better adjustment possibilities to shocks, and net of the fixed costs to be incurred with the tax payment. A firm that is characterized with the technology parameter $\beta_{crit}(w)$ expects the benefits under the tax to be equal with those under permit trading.

Based on Eq. (II.9), the empirical analysis requires information on a firm's actual choice, on the benefits it could expect when it chooses permit trading, i.e. how many permits it would receive, and the benefits it would anticipate when paying the tax, i.e. indicators for its potential tax refund and its flexibility-uncertainty level.

II.5 Data and Variables

The empirical analysis of firms' instrument choices is based on firm-level data from Switzerland's manufacturing industries. The data were obtained from a survey conducted in the fall of 2009 for a research project on the effects of Swiss climate policy on firms (Oberauner and Krysiak, 2010). The survey covered firms with a minimum of 30 employees from manufacturing industries that are located in the German-speaking part of Switzerland.[12]

The survey sample was constructed on the basis of four sources. The first and main source is a random draft of the Swiss Federal Statistical Office (FSO) from September 2009, drafted proportional to grouped employees and industries (FSO survey sample). Second, a selection of emissions trading firms was added (published in the national emissions trading registry), to increase the share of these firms in the sample. Third and fourth, firms listed at the SIX Swiss Exchange and a selection of ISO-14001 certified firms were integrated, as such firms were more likely to provide the related key figures. Except for the firms that were obtained from the FSO, selection problems arose. It was not possible to ensure conformity in all the criteria specified for the survey.

By fall 2009, 1,829 firms were surveyed by means of a written questionnaire; 125 responded to our survey inquiry. Out of the response sample, 72 firms were left that met the requirements for our analysis and could unambiguously be assigned to either the tax or permit trading (response sample). Due to missing values in some of the explanatory variables, and depending on the specification estimated, further observations were dropped by listwise deletion.

Figures II.1 and II.2 illustrate the distributions of employees and industry affiliation for the FSO survey and the response sample. We only consider the FSO survey sample for comparisons, as it comprises more than 70 percent of the firms surveyed

[12]Only manufacturing firms were taken into account, as they are more concerned with climate policy issues than, for example, the service industries (the involved industries are listed in Table II.3 in Appendix II.A.1). To avoid any distortions occasioned by translation, only firms in the German-speaking part of Switzerland were considered. We chose firms with staff of not less than 30 employees in order to increase the likelihood that the required data would be available for these firms.

and as information on labor staff and industry affiliation was not available for the remaining sources.

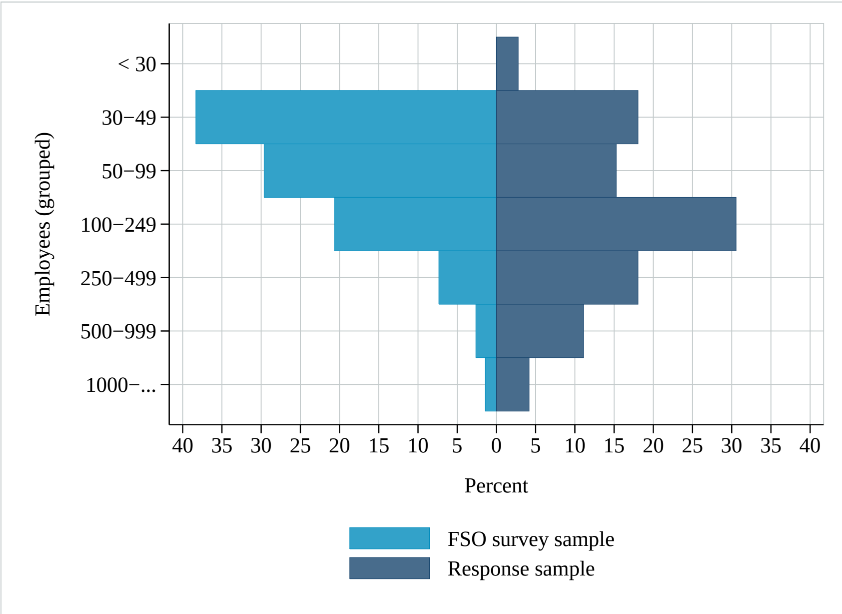

Figure II.1: Distributions of firms' (grouped) employees in the FSO survey and the response sample.

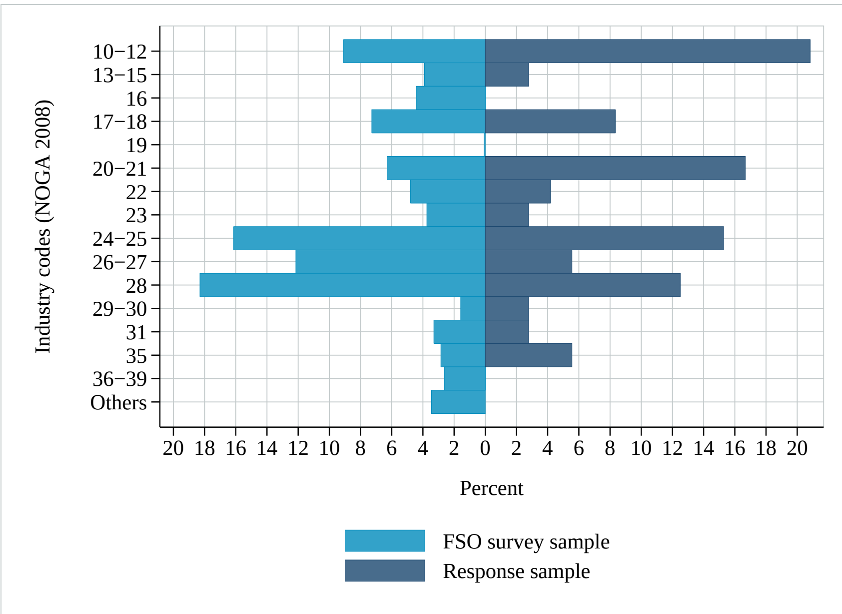

Figure II.2: Distributions of firms' industry affiliations in the FSO survey and the response sample.

Small firms are underrepresented in our analysis.[13] Distributions of firms' industry affiliations are quite similar. Only the shares of the food, beverages and tobacco industries and the chemical and pharmaceutical industries are disproportionately high in the response sample, whereas energy provision, water provision and treatment and the manufacture of wood products are underrepresented.

Testing the theoretical model of Section II.4 – and more precisely to predict instrument choice according to the decision criterion in Eq. (II.9) – data on the chosen regulatory instrument, the potential allocation of permits to all firms, firms' gross wages to indicate the tax refund to all firms, as well as measures of the technological flexibility in adjusting emissions to shocks and of firms' exposure to uncertainty were needed. Questionnaire design specifics and data transformations on these variables are briefly sketched below and summarized in Table II.1.

Table II.1: List of variables.

Variable	**Label**
Instrument	Dummy variable indicating instrument choice (1=emissions trading, 0=tax)
Emissions	Permit allocation proxy: emissions in 2008 in tons divided by sales in 2008 [million Swiss francs]
Wages	Tax refund indicator: gross wages in 2008 [million Swiss francs] divided by sales in 2008 [million Swiss francs]
$Flex * Uncert$	Multiplicative term of two composite variables that indicate (1) firms' flexibility of abatement technologies in adjusting emissions to abatement cost shocks (*Flex*), and (2) firms' exposure to uncertainty in abatement costs (*Uncert*)
Abate_low	Dummy variable indicating low overall abatement in 2008 (less than 5 %) – reference dummy
Abate_mod	Dummy variable indicating moderate overall abatement in 2008 (5 – 19 %)
Abate_high	Dummy variable indicating high overall abatement in 2008 (20 % or more)
LnSales	Natural logarithm of sales in 2008 [million Swiss francs]

First of all, the variable *Instrument* indicates instrument choice and serves as the dependent variable in the empirical analysis. Since two instruments are offered by the Swiss Confederation, *Instrument* is a binary variable and coded to be 1 if a

[13] Larger firms may be better informed and may collect more data on climate-related issues, thereby facilitating questionnaire completion.

firm participates in emissions trading and 0 if a firm pays the tax.

The dependent variable is constructed based on three survey questions, formulated to identify the instrument assignments as being mutually exclusive. Firms were queried on exemption from the tax, on participation in one of the models provided by the EnAW (see Footnote 4) and, finally, on participation in permit trading. Firms have to pay the tax whenever they purchase fossil fuels. So, they must become exempted from it in order to avoid being within the tax regime. Only firms that participate in the Energy Model are entitled to permit trading. The question on participation in permit trading serves to ensure correct instrument assignment.

Second, data on the allocation of permits in 2008 were, by nature, only available for firms involved in permit trading. The correlation between the allocation of permits to firms in emissions trading and CO_2 emissions in 2008 was, however, almost perfect, so, the latter serves as a proxy for potential permit allocation in 2008 for all firms.[14] In turn, CO_2 emissions in 2008 in tons were divided by the sales in 2008 to correct for scale effects. This emissions intensity measure is denoted by the variable $Emissions$.

Third, firms were asked for their gross wages in 2008 to measure the influence of the wage-based tax refund on instrument choice. Again, we corrected for scale effects by dividing them by the sales in 2008. The wage intensity variable is denoted by $Wages$.

Finally, to verify whether there is a flexibility-uncertainty advantage under the tax, the composite variables $Flex$ (to measure flexibility) and $Uncert$ (to measure uncertainty) were constructed. Both variables are multiple-indicator measures derived from the four Likert items: fuel prices, input prices, output demand and breakdown of production equipment. A five-point scale was employed to indicate the flexibility of a firm's technology to adjust emissions to shocks and its exposure to fluctuations with regard to each item. The scores of the items were averaged to

[14] CO_2 emission data were also available for the year 2006, i.e. before climate policy was announced by the regulator. The correlation between emissions in 2006 and the allocation of permits in 2008 amounts to 0.9919. However, some observations would have been dropped using this proxy due to missing values. Besides, CO_2 emissions of firms that were allocated permits in 2008 are published in the national emissions trading registry, operated by the Swiss Federal Office for the Environment (2010b). Thus, data quality could have been improved by correcting for errors and missing values when the firm's identity was known. For these reasons, we preferred to use 2008 emissions data, i.e. when climate policy measures were already implemented (the correlation coefficient between 2006 and 2008 emissions data amounts to 0.9816). The correlation between CO_2 emissions in 2008 and permit allocation in 2008 for firms participating in emissions trading and observations used to estimate the empirical model specifications of Section II.6 is 0.9891.

form a flexibility and a uncertainty score for each firm. 5 represents the highest level of flexibility/exposure to uncertainty and 1 the lowest. What matters for testing the theoretical model, is the multiplicative term of $Flex$ and $Uncert$ labeled as $Flex * Uncert$.

To control for further influencing factors, sales in 2008 ($LnSales$) and the overall abatement activity were included in the empirical model. The natural logarithm of sales in 2008 serves to detect potential scale effects in instrument choice. With regard to abatement, firms were asked on a seven-point response scale to report their overall abatement of CO_2 emissions in 2008 compared to a situation with no abatement at all. The scale was reduced to three categories with a dummy variable constructed for each category: (1) *Abate_low* indicating abatement lower than 5 percent (reference category); (2) *Abate_mod* indicating abatement between 5 and 19 percent; and (3) *Abate_high* indicating abatement of 20 percent and above.

The small size of the sample and the wide range of industry classes (see Table II.3 in Appendix II.A.1) made it impossible to reliably control for industry-specific effects. Moreover, since the data on emissions intensities are significantly non-homogeneous within a class of industry[15], even the use of a dummy variable on emissions-intensive industries is considered inappropriate. For example, although the pharmaceutical industry is associated with emissions-intensive industries, it also covers firms with low intensity. This might be attributable, for example, to fuel substitution or to a firm's core business operating at a low-emission stage in the production chain. Therefore, we consider firm-level comparisons based on emissions intensities, i.e. by the variable $Emissions$, to be more adequate than any comparisons based on industry affiliation.

II.6 Results and Discussion

The full sample used for the empirical analysis consists of 30 firms that participate in emissions trading and 42 that pay the tax. Because of missing values, the listwise deletion procedure reduced the sample size conditional on the explanatory variables involved.

Due to the binary character of the dependent variable $Instrument$, a logit model

[15] The ranges of the reported emissions intensities are seriously high within all classes of industries.

is used for estimation. Thus, in our empirical model, the conditional probability of choosing emissions trading has the form

$$\begin{aligned} Pr(Instrument_i = 1|\mathbf{x}) =& \Lambda(\beta_0 + \beta_1 * Emissions_i + \beta_2 * Wages_i \\ & + \beta_3 * Flex * Uncert_i + \beta_4 * Abate\_mod_i \\ & + \beta_5 * Abate\_high_i + \beta_6 * LnSales_i), \end{aligned} \tag{II.10}$$

with $\Lambda(\cdot)$ as the cumulative distribution function of the logistic distribution.

Our theoretical model predicts a positive influence of *Emissions* on instrument choice, i.e. when the allocation with free permits is increased, the probability of choosing emissions trading is expected to rise. Hence, we expect a positive value for the estimated coefficient. In contrast, firms benefit from a high tax refund when wages are high, making the tax more attractive. The coefficient's sign for *Wages* is therefore expected to be negative. Theory also suggests a negative effect of the flexibility-uncertainty level ($Flex * Uncert$) on firms' preferences for emissions trading. The remaining control variables included in the empirical model are the abatement dummies and the log-transformed sales. Descriptive statistics on these variables are listed in Table II.4 in Appendix II.A.2 for various model specifications.

The results of the logit estimation with all the explanatory variables included are presented in the first column of Table II.2. The coefficients of *Emissions* and *Wages* exhibit the correct signs and are statistically significantly different from zero at the 1 percent level for *Emissions* and at the 5 percent level for *Wages*. This is not true, however, for $Flex * Uncert$ and for *LnSales*. The z-values do not indicate a reliable influence on instrument choice for these variables.[16] Concerning the latter, scale effects in firms' preferences are, thus, not to be observed.

[16] Alternative measures of *Flex* and *Uncert* were used to test the model. Among others, dummy variables were constructed from validity questions that directly asked about flexibility of abatement technologies and uncertainty in abatement costs. All alternative measures had one thing in common with the actual measures used, *Flex* and *Uncert*: the coefficients' signs and the z-values do not indicate a statistically significant and monotonously increasing influence of flexibility and uncertainty on the predicted probability of choosing the tax. The effects of these alternative measures exhibit, however, robustness in the residual variables with regard to sign, significance and magnitude of coefficients.

Table II.2: Logit regression for instrument choice.

	Model 1 *Instrument*	Model 2 *Instrument*	Model 3 *Instrument*
Emissions	0.104***	0.107***	0.116***
	(3.04)	(3.12)	(3.39)
Wages	-22.70**	-26.09**	-27.01***
	(-2.08)	(-2.53)	(-2.74)
*Flex*Uncert*	0.130	0.132	
	(0.85)	(0.85)	
Abate_low	*reference*	*reference*	*reference*
Abate_mod	3.573	3.853*	4.510**
	(1.55)	(1.78)	(2.14)
Abate_high	4.039*	4.188*	5.077**
	(1.70)	(1.87)	(2.29)
LnSales	0.247		
	(0.73)		
Constant	-3.615	-2.084	-1.495
	(-1.09)	(-0.86)	(-0.63)
Observations	62	62	72
p-Value (F-Test)	0.000	0.000	0.000
Pseudo R^2	0.610	0.604	0.628
Count R^2	0.887	0.871	0.875

z statistics in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

With respect to the negative influence of the flexibility-uncertainty level on choosing emissions trading – as suggested by the theoretical model – evidence cannot be provided using the Swiss data. This may be attributed to the fact that in Switzerland not only the permit price is uncertain but also the tax rate. If the national emission reduction targets could not be achieved in previous years, the tax rate is subsequently gradually increased. Indeed, in 2010 the tax rate was increased from 12 Swiss francs in 2008 and 2009 to 36 Swiss francs (see Section II.3 and Footnote 5). So, when choosing an instrument for several periods, Swiss firms are not only subject to price uncertainty in the permit trading regime, but also in the tax regime. Hence, given the specific design of the tax rate in Switzerland, uncertainty concerns are not an issue in instrument choice when firms were the ones to decide on the instrument.

In turn, in Model 2 and Model 3, we re-estimated a reduced specification omitting $LnSales$ in the former, and both, $LnSales$ and $Flex * Uncert$, in the latter, leading to a larger sample size in Model 3.[17] Compared to the Model-1 specification, we

[17] A Likelihood-Ratio test indicates that the variables $LnSales$ and $Flex{*}Fluc$ should be removed

observe robust results for the emissions and wage intensity (both on a 1 percent significance level). In addition, overall abatement in 2008 indicates a statistically significant, positive influence on instrument choice at the 5 percent level in the reduced model. So, firms tend to opt for emissions trading when abatement efforts are relatively high. However, theory would suggest that the rational firm sets marginal abatement costs (marginal savings from emitting) equal to the price or to the tax and solves for optimal abatement (emissions). With regard to expectations, optimal abatement (emissions) is (are) the same for both instruments. So, from a theoretical point of view, variances in abatement efforts should not be an issue with respect to instrument choice.

One possible reason for this result might be that firms participating in permit trading have the prospect of being able to bank their permits beyond the Kyoto period, i.e. beyond 2012.[18] Legislation on Swiss climate policy might be more restrictive in future periods, i.e. the tax might be increased and the cap for permits might be reduced. Moreover, the free permit allocation mode might be partly substituted by auction (Swiss Federal Council, 2009). In addition, the Swiss Confederation intends to link up the national emissions trading system with the system run by the European Union (EU ETS) no later than 2013 (Swiss Federal Office for the Environment, 2009). A more restrictive policy in the European Union after the Kyoto period may force Swiss policy design to become more stringent in order to be accepted for linkage by the European Commission. These aspects might induce permit trading firms to increase abatement efforts today to build up a bank of permits for future policy periods. Inter-period banking with a 1-to-1 permit ratio may, however, be an obstacle to linking up with the EU ETS.

Our empirical model (Model 3) has a high predictive power. Instrument choice is correctly classified (i.e. predicted choice corresponds to observed choice as expressed by Count R^2) in 87.5 percent of the cases.[19] So, for the firms incorrectly classified ($1 -$ Count R^2), unobserved factors are crucial. For firms incorrectly classified in the trading regime, these may be the fixed costs that are substantial under permit trading (see Footnote 7). High fixed costs may lead some (probably relatively small)

from the model.

[18]Banking to periods beyond 2012 is not established by law so far. However, the Swiss Federal Office for the Environment (2007b) specifies the prospect of banking in its commentary on the CO_2 ordinance (CO_2-Verordnung). Additionally, the Swiss Federal Council (2009) documents the possibility of banking in its proposal to the revision of the CO_2 Act.

[19]Firms were classified as being 1 (i.e. emissions trading) if their predicted probability was above 0.5. Classification towards the tax then consistently indicates a predicted probability equal to or below 0.5.

firms to choose the tax that would have preferred the trading regime otherwise. For firms incorrectly classified in the tax regime, one might put forward three arguments. First, firms may have expected to gain from an overallocation in the trading regime due to a lower production induced by the economic recession. However, data of our empirical analysis refer to the year 2008 with firms' instrument decisions met at a point in time[20] when the first signs of the economic recession were observable, but not its actual dimension. Second, some municipalities and power companies grant discounts to firms affiliated with the Energy Model (see Footnote 4), e.g. when purchasing electricity (Energy Agency for the Economy, n.d.). Third, firms in emissions trading benefit from instrument choice flexibility. Non-compliance is sanctioned with a tax payment on every ton of CO_2 emitted (Swiss Federal Assembly, 1999). This means that, large firms in particular, for which trade-specific fixed costs are relatively small, may benefit from selling their permits and paying the tax for their emissions, when the realized permit price is above the tax rate.

The outstanding model fit indicates that our empirical model covers the most influential determinants of instrument choice; moreover, it only requires a few variables to predict firms' preferences between a tax and permit trading correctly with a high degree of probability. So, for a regulator implementing a self-selection mechanism, the task of estimating firms' choices and influencing the outcome by setting the policy variables appropriately is relatively easy.

As the coefficients of Model 3 in Table II.2 represent logits that do not have an intuitive interpretation, we illustrate the dependency of the predicted probabilities on the emissions and on the wage intensity for reference values of the remaining variables in Figures II.3 and II.4, respectively.

Figure II.3 depicts the positive relationship between the emissions intensity and the probability of choosing emissions trading for reference values of the wage intensity. Thus, as the ratio of CO_2 emissions to sales increases, firms benefit from a higher allocation with free permits, making emissions trading more attractive. If the wage intensity is low, then even a relatively low level of emissions intensity suffices for the gain from the tax refund to be outweighed by the benefits from permit trading. By contrast, firms with a high wage intensity prefer the tax, except when the emissions intensity is at a relatively high level. Then, the tax refund is high and firms are better off under permit trading only when their allocation of permits is at a high level.

[20]Submission deadline for applications for exemption from the tax for the year 2008 was September 1, 2007 (Swiss Federal Council, 2007).

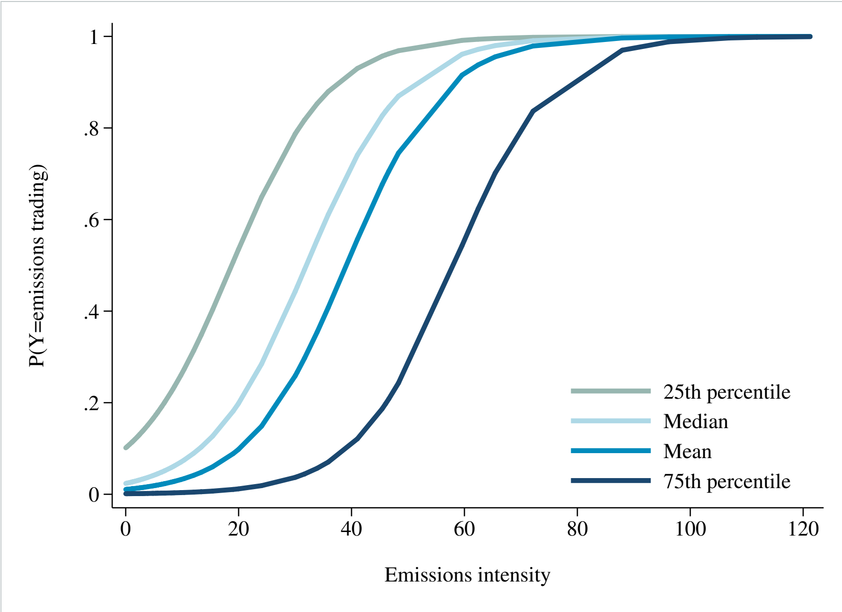

Figure II.3: The probability of choosing emissions trading conditional on the emissions intensity for various levels of the wage intensity, while holding the abatement dummies constant at their respective mean values (Model 3); the wage intensity for the reduced sample is positively skewed, thus, the median of the wage intensity lies above its mean.

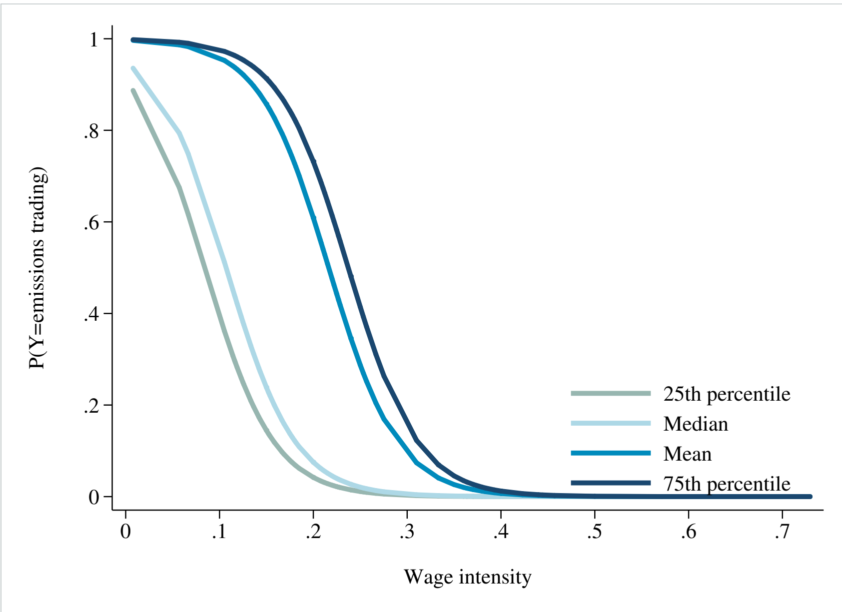

Figure II.4: The probability of choosing emissions trading conditional on the wage intensity for various levels of the emissions intensity, while holding the abatement dummies constant at their respective mean values (Model 3); the emissions intensity is even more positively skewed than the wage intensity.

Figure II.4 draws the same picture for the probability of choosing emissions trading conditional on the wage intensity for various levels of the emissions intensity. The higher a firm's wage intensity, the higher is the probability of choosing the tax. For firms at a low level of emissions intensity, the probability of opting for the tax increases when wages increase. Thus, firms with a low level of potential permit allocation are better off with a tax, due to the relatively high refund of tax payments. Firms with a relatively high emissions intensity, by contrast, will only be willing to choose the tax when their wage intensity is comparatively high and the tax refund outweighs the value of the potential permit allocation.

Figures II.3 and II.4 not only reflect the empirical evidence of the theory with regard to emissions and wages presented in Section II.4, but also confirm that firms behave as suggested by the Swiss Federal Office for the Environment (2007a), which recommends participation in emissions trading whenever firms exhibit high CO_2 emissions in conjunction with low wages and a tax payment in the reverse situation.

Table II.2 presents the results of the logit estimation for all firms in the sample, no matter how much CO_2 they emit and independent of firm size. Firms that exhibit energy costs of at least 200,000 Swiss francs are unrestrictedly permitted to participate in emissions trading when they decide on the quantity regime (Energy Agency for the Economy, n.d.). In contrast, for small- and medium-sized firms, the Swiss Confederation established quantity targets that correspond to a mixture of a performance-based standard and emissions trading (see Section II.3, and in particular Footnote 4). Firms with energy costs below 200,000 Swiss francs do not receive free permits and have no incentive to overcomply with their reduction target. But they are permitted to cover their excess emissions with permits purchased on the permit market in case they should fail to reach their quantity targets. Therefore, freedom of instrument choice between the tax and permit trading is not guaranteed in the sample used for the Model-3 specification.

Restricting our sample to only those firms that are completely free to choose between the tax and permit trading leads to an increased preference towards emissions trading.[21] This effect is relatively weak and may not carry over when applied to even small- and medium-sized firms, as only large emitters are considered in our freedom-of-choice sample. Fixed costs associated with participating in emissions trading are substantial compared to the tax (see Footnote 7), shrinking the benefits of free permit allocation.

[21]The freedom-of-choice estimation results are presented in detail in Appendix II.A.3.

II.7 Conclusions

In our paper, we empirically investigate firms' preferences in their choice between a tax and permit trading when the regulatory authority delegates instrument choice to firms. Such a self-selection mechanism is implemented on firms' carbon dioxide emissions in Switzerland. With Swiss firm-level data, we were, thus, able to contribute to the prices-vs.-quantities literature with an empirical study on instrument choice from the perspective of firms.

The theoretical framework for our analysis is provided by Krysiak and Oberauner (2010). When there is uncertainty with regard to firms' abatement costs and, in addition, asymmetric information between the regulatory authority and the firms, they show that a "Policy à la Carte" (i.e. a policy mechanism that is based on firm self-selection between a tax and permit trading) dominates a single instrument regime in expected welfare terms. Based on this theoretical approach and taking specific Swiss climate policy characteristics (pure grandfathering of permits, wage-based tax refund for taxpaying firms) into account, firms' instrument preferences were empirically analyzed using Swiss firm data.

From a theoretical point of view, firms prefer emissions trading whenever the expected benefits of trading (the value of potential permit allocation minus trade-specific fixed costs) outweigh the expected benefits of paying the tax (the tax refund, plus a flexibility-uncertainty advantage of the tax, and minus tax-specific fixed costs).

The empirical results indicate that the potential permit allocation and the wage-based tax refund are indeed crucial in a firm's choice of instrument. If a firm's wages are low – and in turn a firm's tax refund – then the benefits under the price regime are more easily compensated for by the benefit of free permits in emissions trading, leading firms to prefer the quantity instrument. If, however, firms have high wages and also expect only a low allocation with permits, then they tend to prefer the price regime, due to a more dominant tax-refund incentive.

In contrast to our findings regarding permit allocation and the tax refund, we are not able to provide empirical evidence in support of the theoretical model with respect to the flexibility-uncertainty advantage under the tax that derives from the better adjustment possibilities of emissions to shocks. The famous finding of Weitzman (1974) that in the presence of uncertainty in abatement costs the choice between a price and a quantity instrument matters, does not carry over when instrument choice is left to the firms. In our empirical analysis, firms' preferences between a tax and emissions trading are unaffected by their exposure to uncertainty. However, this may be a result that is specific to Swiss firms as they face price uncertainty under both regimes.

Furthermore, and contrary to theoretical predictions, firms' instrument decisions are influenced by their abatement activity: High-abatement firms prefer participation in emissions trading, a result that may be attributed to the banking of permits beyond the Kyoto period.

Overall, the estimation of our empirical model results in a convincing model fit, although covering only a few, but the most influential variables. Thus, with only a little information on firms, we were able to predict a firm's choice for one of the instruments correctly with a high degree of probability. Given these results, a regulator can easily estimate how firms are likely to behave given that she possesses the necessary key facts on firm characteristics so that she is able to adjust existing policies or to design future policies in order to achieve a high level of efficiency.

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II.A Appendix

II.A.1 Industry Classes

Table II.3: NOGA 2008 General Classification of Economic Activities (Swiss Federal Statistical Office, 2008).

Code	Industry
10	Manufacture of food products
11	Manufacture of beverages
12	Manufacture of tobacco products
13	Manufacture of textiles
14	Manufacture of wearing apparel
15	Manufacture of leather and related products
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
17	Manufacture of paper and paper products
18	Printing and reproduction of recorded media
19	Manufacture of coke and refined petroleum products
20	Manufacture of chemicals and chemical products
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Manufacture of rubber and plastic products
23	Manufacture of other non-metallic mineral products
24	Manufacture of basic metals
25	Manufacture of fabricated metal products, except machinery and equipment
26	Manufacture of computer, electronic and optical products
27	Manufacture of electrical equipment
28	Manufacture of machinery and equipment
29	Manufacture of motor vehicles, trailers and semi-trailers
30	Manufacture of other transport equipment
31	Manufacture of furniture
32	Other manufacturing
33	Repair and installation of machinery and equipment
35	Electricity, gas, steam and air conditioning supply
36	Water collection, treatment and supply
37	Sewerage
38	Waste collection, treatment and disposal activities; materials recovery
39	Remediation activities and other waste management services

II.A.2 Descriptive Statistics

Table II.4: Descriptive statistics conditional on model specification.[22]

	Obs.	Mean	Std.Dev.	Min	Max
Model 1 and 2					
Instrument	62	0.419	0.497	0	1
Emissions	62	32.654	58.614	0.015	287.692
Wages	62	0.238	0.133	0.008	0.730
*Flex*Uncert*	62	9.034	3.631	1.5	17
Abate_mod	62	0.435	0.500	0	1
Abate_high	62	0.306	0.465	0	1
LnSales	62	4.153	1.666	1.501	9.852
Model 3					
Instrument	72	0.417	0.496	0	1
Emissions	72	33.631	56.071	0.015	287.692
Wages	72	0.240	0.127	0.008	0.730
Abate_mod	72	0.417	0.496	0	1
Abate_high	72	0.306	0.464	0	1
Model 4 and 5					
Instrument	42	0.619	0.492	0	1
Emissions	42	46.056	67.241	1.073	287.692
Wages	42	0.216	0.120	0.008	0.571
*Flex*Uncert*	42	9.447	3.557	1.667	17
Abate_mod	42	0.500	0.506	0	1
Abate_high	42	0.333	0.477	0	1
LnSales	42	4.650	1.598	1.589	9.852
Model 6					
Instrument	51	0.588	0.497	0	1
Emissions	51	45.682	62.771	1.073	287.692
Wages	51	0.222	0.115	0.008	0.571
Abate_mod	51	0.471	0.504	0	1
Abate_high	51	0.314	0.469	0	1

[22]The mean of the dependent variable *Instrument* indicates the percentage of firms in emissions trading for the respective specification.

II.A.3 Results from a Freedom-of-Choice Estimation

Specifications of Model 4, 5 and 6 in Table II.5 are the freedom-of-choice analogues of Model 1, 2 and 3 (for the descriptive statistics see Table II.4 in Appendix II.A.2). Hence, observations used in Model 6 are a subsample of the observations used in Model 3. All permit trading firms are still in the sample as they fulfill the criteria for freedom of instrument choice anyway. However, the subsample includes only those taxpaying firms that exhibit energy costs above 200,000 Swiss francs and were, thus, unrestrictedly free to choose permit trading.

Table II.5: Logit regression for instrument choice with freedom of choice.

	Model 4 *Instrument*	Model 5 *Instrument*	Model 6 *Instrument*
Emissions	0.0798**	0.0796**	0.0892***
	(2.48)	(2.47)	(2.79)
Wages	-20.11*	-21.20**	-21.43**
	(-1.95)	(-2.18)	(-2.37)
*Flex*Uncert*	0.136	0.135	
	(0.84)	(0.82)	
Abate_low	*reference*	*reference*	*reference*
Abate_mod	2.920	2.980	3.758**
	(1.44)	(1.49)	(2.03)
Abate_high	3.831*	3.914*	4.907**
	(1.77)	(1.84)	(2.39)
LnSales	0.103		
	(0.28)		
Constant	-2.129	-1.463	-1.107
	(-0.66)	(-0.67)	(-0.51)
Observations	42	42	51
p-Value (F-Test)	0.000	0.000	0.000
Pseudo R^2	0.502	0.500	0.557
Count R^2	0.857	0.857	0.863

z statistics in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The signs of the estimated logits are the same for both classes of specifications, i.e. with and without restrictions in freedom of choice. But there are small differences in the statistical significance and in the magnitude of the coefficients. Again, $Flex * Fluc$ and $LnSales$ are omitted from the full model with freedom of choice (Model 4) for the same reasons as above, which results in the Model-6 specification. Goodness of fit in Model 6 (expressed by Count R^2) is only less than one percentage point lower in the freedom-of-choice specification, whereas the Pseudo R^2 increases. Hence, by and large, robustness in the results can be observed. Freedom of instrument choice enhances the predicted preferences of firms towards emissions trading – which is a natural result of abolishing the restriction in choice – but this only to a small degree. There are only two firms classified under emissions trading that would have preferred the tax with Model-3 estimation.

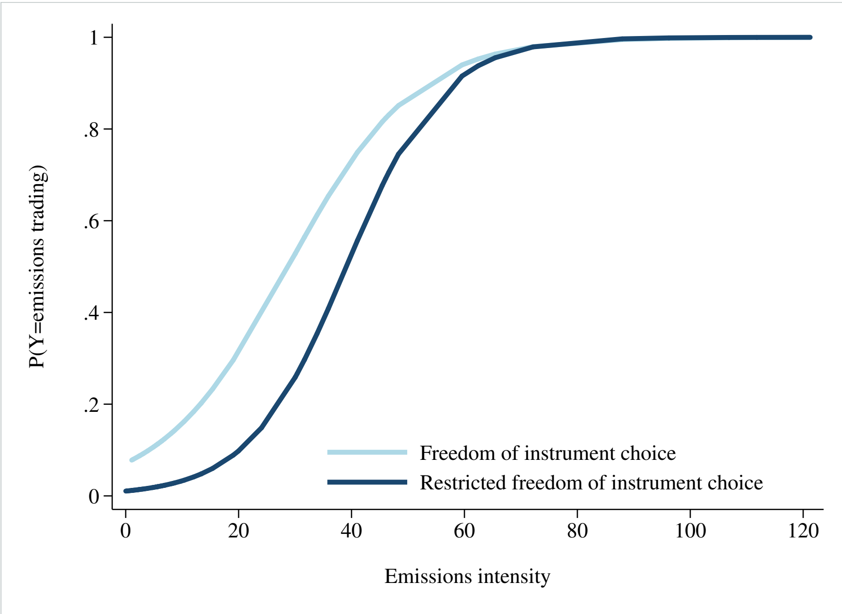

Figure II.5: The probability of choosing emissions trading conditional on the emissions intensity with restricted and unrestricted freedom of choice, holding the wage intensity and the abatement dummies constant at their respective mean values (Model 3 and 6).

The graphical representations of the effect of freedom of choice on the predicted probabilities are displayed in Figures II.5 and II.6. When firms are free to choose between the instruments, the probability of choosing emissions trading is higher for all levels of emissions intensity (Figure II.5). Analogously, if we plot the probability curve as being dependent on the wage intensity (Figure II.6), the freedom-of-choice cumulative distribution function is always above the one with restrictions.

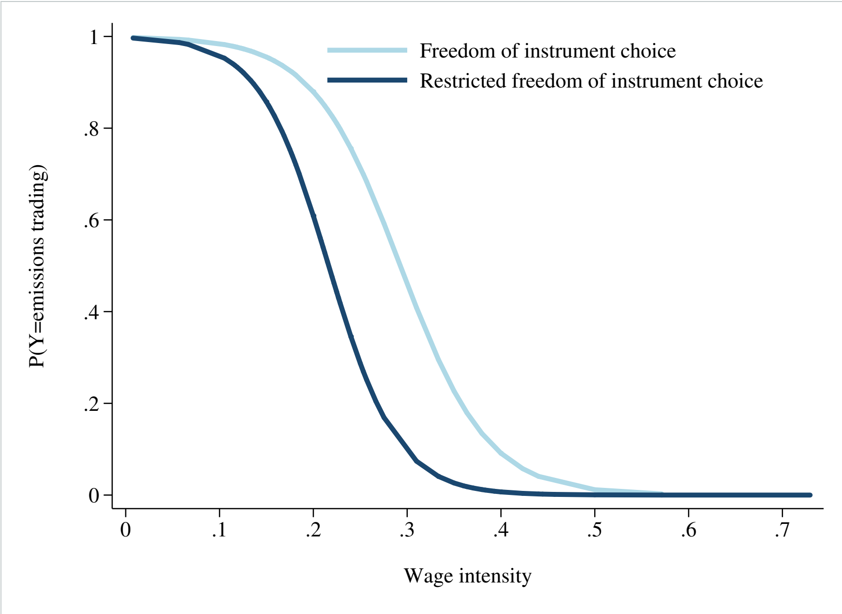

Figure II.6: The probability of choosing emissions trading conditional on the wage intensity with restricted and unrestricted freedom of choice, holding the emissions intensity and the abatement dummies constant at their respective mean values (Model 3 and 6).

Essay III

Abatement Technology Adoption under Different Policy Regimes: Some Empirical Evidence

Iris Maria Oberauner

University of Basel, Faculty of Business and Economics, Department of Environmental Economics, Peter Merian-Weg 6, 4002 Basel, Switzerland, *Iris.Oberauner@unibas.ch*

Abstract

Based on survey data of Swiss manufacturing firms, we empirically investigate the incentives provided by different policy instruments for firms to invest in abatement technologies. More specifically, we compare a tax and emissions trading. In Switzerland, both instruments are used simultaneously to regulate carbon dioxide emissions. Therefore, we are able to analyze possible differences regarding the investment incentives induced by these instruments. The results from a bivariate and multivariate analysis indicate the superiority of free permits over an emissions tax in promoting abatement technology adoption, a result that is diametrically opposed to the traditional theoretical result.

Keywords: Abatement Technology Adoption, Prices vs. Quantities, Emissions Tax, Emissions Trading, Swiss Climate Policy

JEL classification: Q55, Q58, Q54, O33, O38

III.1 Introduction

It is well known that in a *static* framework market-based instruments, like an emissions tax or permit trading, dominate command and control policies (CAC) for regulating harmful emissions in terms of cost efficiency. From a *dynamic* point of view, the criteria by which environmental policy instruments may be judged are the incentives they provide to spur the use of advanced abatement technologies (Kneese and Schultze, 1975). While the spectrum of theoretical research is extensively elaborated in both contexts, empirical studies are rare. In particular, the differential impacts of different policy regimes on technological change are a widely unexplored field of empirical research. Our current study attempts to contribute to this stream of literature by providing an empirical study on the behavior of firms in adopting new abatement technologies when they are regulated either by an emissions tax or else by emissions trading. Swiss carbon dioxide mitigation strategies provide an optimal policy framework for investigating this research question. Here, firms can choose between an emissions tax and permit trading. By accounting for self-selection, the differential impacts on technology adoption can be analyzed under otherwise equal economic conditions.

There is a comprehensive theoretical literature on the relative merits of prices vs. quantities with respect to their impacts on firms' adoption decisions concerning abatement technologies (see, for example, a review by Requate, 2005). The traditional result of the theoretical literature signifies that a tax provides stronger incentives to adopt new abatement technologies than free permits (e.g. Milliman and Prince, 1989; Jung et al., 1996).

In contrast to the theoretical research, little is known about the differential impacts of employing an emissions tax vs. tradeable permits in promoting technology adoption in practice. The main reason is that there are hardly any environmental policy designs implemented in practice that provide a regulatory framework appropriate for answering the current research question. Ideally, there would be an economy in which one group of firms is regulated with a tax, while the other group is regulated by emissions trading with the instruments being assigned randomly. With its implementation of active climate policy measures in 2008, Switzerland is close to achieving these ideal conditions. The Swiss Confederation established a "Policy à la Carte" (Krysiak and Oberauner, 2010) that consists of a tax on carbon dioxide emissions and a system of tradeable permits (grandfathering), from which firms can choose their preferred instrument. By using data from Swiss manufacturing firms, we were thus able to identify the instruments' differential impacts on abatement technology adoption with all other economic conditions being equal. In order to avoid any bias from the self-selection of instruments, we use an econometric procedure in our empirical analysis that accounts for endogeneity.

Swiss climate policy not only offers an outstanding opportunity to answer the current research question, but also permits an empirical investigation of prices vs. quantities issues in environmental regulation in general. This research could produce important insights that can be applied to future environmental policy designs. Oberauner (2010) provides the first research contribution on this topic that uses Swiss data. In her empirical study, she explores the instrument preferences of firms when they can self-select between a tax and permit trading.

The results of our current empirical analysis indicate that a system of tradeable permits induces stronger incentives for abatement technology adoption than a tax regime. Both, a bivariate analysis of the investment expenditures for CO_2 abatement technologies under a tax vs. an emissions trading regime, and a multivariate analysis with firms' investment intensities in the first year of climate policy implementation as the outcome variable of interest, lead to this conclusion. While the prevailing view of the theoretical literature emphasizes the dominance of an emissions tax in this context, empirical evidence suggests the opposite. Uncertainty issues, transition effects of policy implementation and different perceptions in the stringency of the instruments might explain our findings. It should be noted, however, that the small sample size restricts the set of statistical methods used to analyze the data and that crucial assumptions underlying the econometric models used are violated. Despite these weaknesses, the results of the empirical analysis are clear, qualitatively robust and based on multiple statistical methods applied to the analysis of the best data available: Tradeable permits dominate the emissions tax in providing incentives for abatement technology adoption.

The paper is organized as follows. In the next section, we briefly review the existing literature on the differential impacts of prices versus quantities in environmental regulation in spurring technological change. Section III.3 introduces Swiss climate policy. Survey issues, data and variables are discussed in Section III.4. The results from the empirical analysis are presented in Sections III.5 and III.6. In a first step, we conduct a bivariate analysis to gain a first impression of the direction of potential instrument-related differences in technology adoption. Then, in a multivariate analysis causal relationships are analyzed to isolate the instrument-related effect. Finally, we conclude in Section III.7.

III.2 Related Literature

Comprehensive literature exists on the impacts of environmental policy instruments on technological change in a theoretical setting. Prominent studies in this field are, for example, those of Mendelsohn (1984), Milliman and Prince (1989), Jung et al. (1996), Requate and Unold (2001), Requate and Unold (2003), and Zhao (2003). A review is provided by Requate (2005).

Mendelsohn (1984) integrates technical change into the prices vs. quantities model of Weitzman (1974). This leads the Weitzman result to shift in favor of the quantity instrument due to excessive levels of emissions, and in turn, excessive levels of technical change under the price instrument.

Both, Milliman and Prince (1989) and Jung et al. (1996), provide rankings in promoting technological change for the main environmental policy instruments when all or none of the firms within an industry adopt the new technology. While the former consider the incentives provided by the instruments to firms, the latter show the results from the perspective of an industry. Both studies favor an emissions tax as opposed to free permits. The new technology reduces marginal abatement costs and consequently, the permit price shifts to a lower level, thereby reducing the incentives for technology adoption. In aggregate, a firm's savings from the new technology are then higher under the tax compared to free permits.

In contrast to this earlier literature, Requate and Unold (2001, 2003) endogenize the number of adopting firms. Depending on the fixed installation costs of the new technology, all or none of the firms adopt under the tax, while among the permit-trading firms all, none or some of them (with some firms free-riding on the decreasing permit price) adopt. Compared to the social optimum, taxes lead to overinvestments; permits lead to underinvestments. If the regulator anticipates the new technology before it is adopted, then permits induce socially optimal adoption. In the case of an emissions tax, under- and overinvestment is possible (Requate and Unold, 2003).

In a general equilibrium framework, Zhao (2003) adds uncertainty considerations to the analysis of a tax and tradable permits in encouraging abatement investments. He shows that firms' investment incentives are more likely to be maintained under a system of tradable permits when shocks lead to abatement cost uncertainties.

In contrast to the theoretical literature, empirical studies on abatement technology adoption under different policy regimes are rare. Jaffe et al. (2002), Vollebergh (2007a), and Vollebergh (2007b), for example, point out that first and foremost data availability limitations are responsible for the lack of empirical evidence. Vollebergh (2007b) reviews the existing empirical literature on the differential impacts of market-based and non-market-based instruments on technological change. Among these is the study by Kerr and Newell (2003). Besides providing evidence of a positive response of regulatory stringency on technology adoption during the U.S. petroleum refinery phasedown of lead in gasoline, the authors observe significantly higher incentives for technology adoption under a regime of tradeable permits compared to a performance standard.

To our knowledge, empirical studies on the differential impacts of an emissions tax and free permits do not exist. Answering the current research question requires that we investigate an economy that makes use of both a tax and an emissions trading system, implemented under similar economic conditions. Such conditions are currently provided by Swiss climate policy.

III.3 Swiss Climate Policy Design

For the Kyoto period, active measures to mitigate climate change were implemented in January 2008 in Switzerland.[1] First and foremost, these measures comprise a tax on carbon dioxide emissions ("CO_2-Abgabe") and a system of tradeable permits.

Private individuals and firms are charged the tax on every ton of CO_2 emitted from the combustion of fossil fuels for heating and energy generation[2], which is deducted directly from the fossil fuel invoice. Starting with a rate of 12 Swiss francs in 2008, the tax is gradually increased when national annual reduction targets are not achieved.[3] The revenues collected from firms are refunded to taxpaying firms proportionally to their gross wages.

[1]Swiss climate policy is primarily legally documented in the Federal Act on the Reduction of CO_2 Emissions (Swiss Federal Assembly, 1999), or short CO_2 Act, and the CO_2 Ordinance (Swiss Federal Council, 2007). The former comprises the CO_2 mitigation strategies and targets; the latter regulates the measures for operationalizing the CO_2 Act.

[2]Carbon dioxide emissions from transport are regulated separately.

[3]While the tax rate remained constant until the end of 2009, the Swiss Confederation raised the levy on carbon emissions to 36 Swiss francs in 2010, as CO_2 emissions from fossil fuel combustion in 2008 were above the predetermined target (Swiss Federal Office for the Environment, 2009).

Yet, firms can gain exemption from the tax when they commit to an ambitious, legally-binding CO_2 reduction target. Tax-exempted large emitters are then allocated a number of emission permits that corresponds to their reduction commitment, with one certificate allowing the owner to emit one tonne of carbon dioxide. Firms are then free to trade their allowances within the national emissions trading system. So, basically, emissions trading in Switzerland is operated in a cap-and-trade style with aggregated individual emission targets from trading firms as the cap and with a grandfathering mode of permit allocation, i.e. based on historic emissions and free-of-charge.[4]

Hence, emitters of CO_2 from fossil fuel combustion are offered the choice between either being regulated by a tax or else by permit trading.[5] This unique and exceptional climate policy design offers an interesting and outstanding field for empirical research: Under equal economic conditions, a price and a quantity instrument are implemented, providing the opportunity to reveal potential differences in their impacts on important economic variables. Firm preferences between the tax and tradeable permits were already investigated by Krysiak and Oberauner (2010) in a theoretical setting and, based on Swiss firm-level data, by Oberauner (2010) in an empirical setting. By using the same firm data, we are able to investigate the differential impacts of prices vs. quantities on technology adoption and thereby advance this important field of empirical research.

[4]The CO_2 Act specifies the criteria for permit allocation to be a firm's historic abatement measures, the costs of abatement measures, the firm's international competitive position, and its expected output growth (Swiss Federal Assembly, 1999). Running a correlation between historic emissions (2006 and 2007) and permit allocation in 2008 yields, however, an almost perfect correlation (correlation coefficients 0.9919 and 0.9915 respectively). Thus, evidence suggests that permit allocation is based solely on historic emissions.

[5]As far as small- and medium-sized emitters are concerned, discrimination in instrument choice prevails. When they choose to gain exemption from the tax, their quantity regulation option is devised as an individual emission standard, and, in case they fail to meet their specific target, they are permitted to buy allowances on the emissions trading market. However, discrimination occurs, as they are prohibited from selling excess emissions on the market (Swiss Federal Office for the Environment, 2010). So, they are only partly linked to emissions trading (conditional on their abatement costs for CO_2 emissions), thereby challenging their integration within our research study. However, survey responses of small- and medium-sized emitters that chose a quantity standard was negligible. So, restricting our sample only to taxpaying firms and firms that are fully involved in permit trading considerably facilitates our analysis. Firm size with respect to the amount of CO_2 emitted, however, is a variable that has to be controlled for in our multivariate analysis to justify this abstraction.

III.4 Data and Variables

For our empirical analysis, we use firm-level data of Swiss manufacturing industries obtained from a survey conducted in fall 2009.[6] The overall survey sample comprised 1,829 firms with a response rate of 7 percent (127 firms). Of these responding firms, 107 firms met the requirements for our statistical analysis. Furthermore, the sample size is reduced depending on the variables used for statistical analysis due to missing values. More details on the survey and the responses are provided by Oberauner and Krysiak (2010) and Oberauner (2010).

From our database, we use data on the investment expenditures for CO_2 abatement technologies, on firms' instrument choices, on their abatement activities, on their CO_2 emissions, and on their wages. Questionnaire specifics and data transformations of these variables are discussed below. An overview is provided in Table III.5 in Appendix III.A.1.

First of all, our data sample comprises investment expenditures for the following three time periods: (1) the time period prior to 2008, i.e. the time in absence of any active climate policy measures; (2) the year 2008, i.e. the first year in which the tax and permit trading were in place; and (3) prospectively for the years 2009 and 2010.[7] Investment expenditures serve as an indicator to measure firms' propensities to adopt advanced abatement technologies, with the 2008 data as our outcome of interest.

We transformed the absolute expenditures data to intensities in order to correct for scale effects, i.e. we constructed ratios based on sales in 2008. The intensities are denoted by $Invest_{hist}$ for the time prior to 2008, $Invest_{08}$ for the year 2008, and $Invest_{fut}$ for the prospective time period 2009/2010. The ratio values are used in both our bivariate and our multivariate analysis. Besides, the log-transform of $Invest_{hist}$ and $Invest_{08}$ were used in our multivariate analysis, with the intensity rations based on sales in million Swiss francs to avoid negative numbers.[8] The natural logarithm of the intensities are analogously denoted by $lnInvest_{hist}$ and $lnInvest_{08}$.

[6] The survey was conducted for a research project to empirically evaluate the effects of national climate policy measures on Swiss firms (Oberauner and Krysiak, 2010).

[7] The last time period is partly forward-looking as the survey was conducted in fall 2009. Nevertheless, it is reasonable to assume that firms pursue their investment plans in the medium run.

[8] For our analysis, we used the user-written Stata command *cmp* (Roodman, 2010) which is not appropriate for Tobit estimation with a lower limit unequal to zero. With this scaling, it was possible to construct a zero lower bound even for the log-transformed intensity data.

Second, a firm's choice of policy instrument shows up in the binary variable $Regime$, with $Regime = 0$ when a firm chose to pay the tax, and with $Regime = 1$ when a firm chose to participate in emissions trading. $Regime$ is constructed based on three questions to unambiguously identify instrument affiliation: Firms were queried on exemption from the tax, on participation in one of the models provided by the Energy Agency for the Economy (EnAW),[9] and on participation in permit trading. Firms have to pay the tax whenever they purchase fossil fuels. Usually, tax exemption goes along with EnAW-model participation with large energy-intensive firms being entitled to permit trading. The question regarding participation in the emissions trading scheme only served to verify whether firms' policy regime affiliations were correctly recorded.

Third, to indicate abatement activity, firms were asked on a seven-point response scale to report overall CO_2 abatement in 2008 compared to a situation with no abatement at all. The answer scale was reduced to three categories with a dummy variable constructed for each category: (1) $Abate\_low$ indicates low abatement (< 5 percent; reference category); (2) $Abate\_mod$ indicates moderate abatement ($5 - 19$ percent); and (3) $Abate\_high$ indicates high abatement levels (≥ 20 percent).

Forth, CO_2 emissions in tons in 2008 relative to sales in 2008 in million Swiss francs are denoted by $Emissions$. This emissions intensity variable serves as a proxy for the potential permit allocation firms would have received under emissions trading (see Footnote 4).

Finally, $Wages$ indicate a firm's potential refund of tax receipts, an incentive provided for firms to choose the tax regime. Therefore, firms' gross wages in 2008 relative to their sales in 2008 were taken. For more details on the construction of $Emissions$ and $Wages$ see Oberauner (2010).

In the next two sections, the empirical analysis results are presented. In a first step, the data on investment expenditures were analyzed using bivariate methods (Section III.5). Then, documented in Section III.6, the causality between the investment expenditures and the regulatory instruments, on the one hand, and other potential influencing factors, on the other hand, were investigated using multivariate methods.

[9]The EnAW serves as an intermediator between the Swiss confederation and firms. It provides three quantitative commitment models to firms. Large energy-intensive firms are intended to join the so called Energy Model in conjunction with permit trading participation. For small- and medium-sized firms, two different models with emissions reduction targets were designated, allowing them only to buy emission allowances when they fail to meet their specific targets (see also Footnote 5).

III.5 Results from a Bivariate Analysis

Due to varying time horizons of the investment intensity data for abatement technologies, interperiod comparisons are not meaningful. We therefore only compare the tax subset with the permit trading subset within the periods in order to detect any significant differences in mean investment expenditures. For the bivariate analysis a Wilcoxen rank-sum test[10] was conducted. The results of this test and measures of central tendency are summarized in Table III.1. The distributions of firms' (grouped) investment intensities are illustrated in Figure III.1 for the subsamples.

Table III.1: Investment intensities in percent: Median (med), mean and Wilcoxon rank-sum test (WRST); observations in subsamples: $Invest_{hist}$: $N_t = 65$, $N_p = 29$; $Invest_{08}$: $N_t = 66$, $N_p = 34$; $Invest_{fut}$: $N_t = 64$, $N_p = 33$. Subscripts t and p denote the tax and permits, respectively.

Variable	$\mathbf{Med}_t$	$\mathbf{Med}_p$	$\mathbf{Mean}_t$	$\mathbf{Mean}_p$	WRST[a]	$P(x\|Regime = 0) > P(x\|Regime = 1)$[b]
$Invest_{hist}$	0 %	0.9823 %	0.9595 %	2.9351 %	0.0000***	24.1 %
$Invest_{08}$	0 %	0.2205 %	0.4937 %	1.3069 %	0.0000***	21.6 %
$Invest_{fut}$	0 %	0.3333 %	1.0113 %	0.8648 %	0.0056***	33.7 %

[a] p value of the Wilcoxon rank-sum test with significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
[b] Probability that the investment intensity from a random draw of the group of taxpaying firms ($Regime = 0$) is larger than from a random draw of the group of permit trading firms ($Regime = 1$).

While the majority of taxpaying firms did not make any CO_2-related investments at all, the majority of trading firms exhibit a positive investment intensity in all time periods. This is not only reflected by the median but also by the mean. The mean investment intensity of trading firms is always higher than that of taxpaying firms except in the period 2009/2010; this, however, is only due to a statistical outlier in the tax subsample with substantial expenditures for CO_2 abatement technologies relative to 2008 sales. In every time period, investment intensities of permit trading firms are significantly higher than those of taxpaying firms at a 1 percent level.

[10] The Wilcoxon rank-sum test is a non-parametric, distribution-free rank-sum test to measure differences in the distribution of two independent populations (tax vs. emissions trading). It tests for differences in location, spread and shape of the distributions (Keller and Warrack, 2003). H_0: The two population distributions are equal. H_1: The distribution of population tax differs from the distribution of population emissions trading.

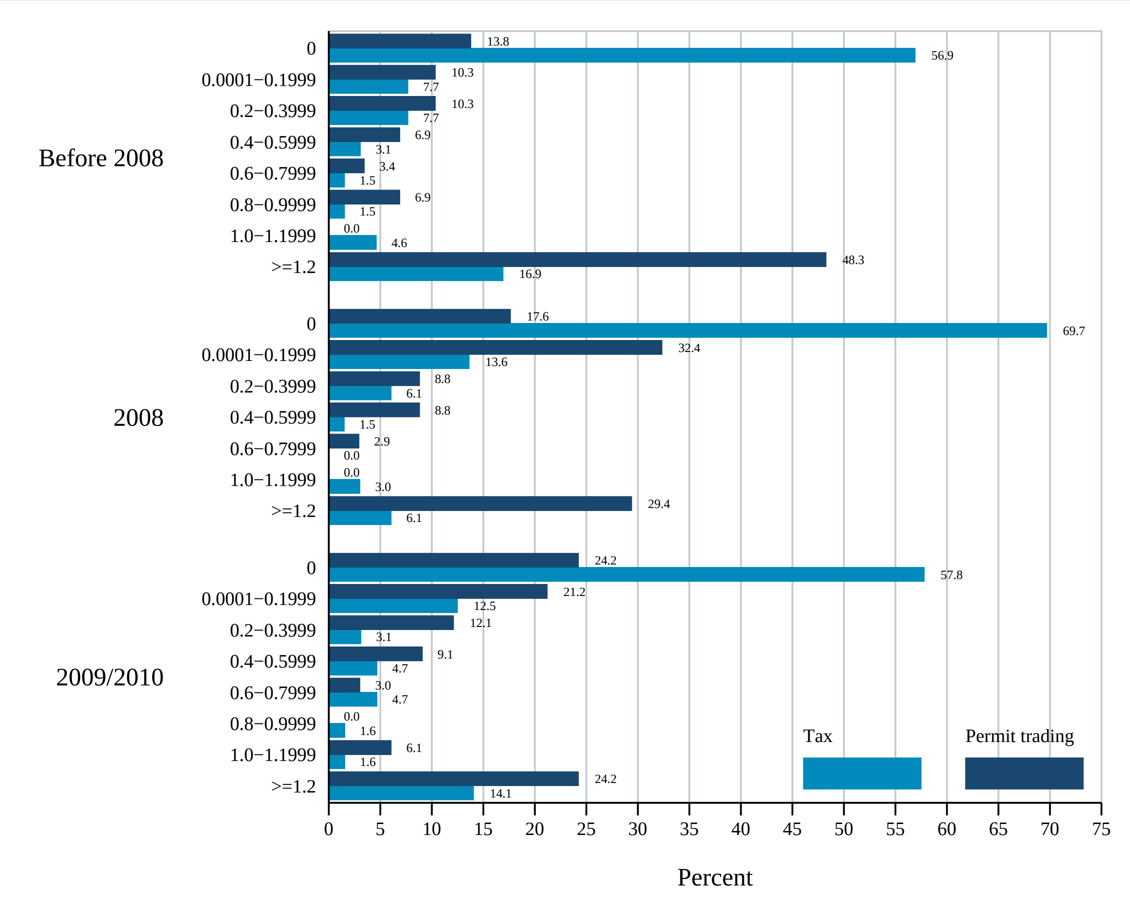

Figure III.1: Firms' intensities of investments in CO_2 abatement technologies (grouped); observations in subsamples: $Invest_{hist}$: $N_t = 65$, $N_p = 29$; $Invest_{08}$: $N_t = 66$, $N_p = 34$; $Invest_{fut}$: $N_t = 64$, $N_p = 33$. Subscripts t and p denote the tax and permits, respectively.

From these results it becomes obvious that there are significant differences in the technology adoption behavior of the two subsets. This effect can be observed, however, independent of climate policy implementation in January 2008. This raises the question of whether policy implementation had an effect on the CO_2-related investment behavior of firms at all, and if so, whether it makes a difference when a firm is either regulated by a tax or else by permit trading. For this purpose, firms were queried on a five-point response scale to classify the effect of climate policy measures on their investment decisions with respect to CO_2 abatement technologies. The bivariate analysis results of firms' responses are presented in the first row of Table III.2; Figure III.2 illustrates how firms' responses are distributed on the response scale.

Table III.2: Investment- and R&D-related effects of climate policy implementation: Median (med) and Wilcoxon rank-sum test (WRST); observations in subsamples: $N_t = 64$, $N_p = 38$. Subscripts t and p denote the tax and permits, respectively. Response scale: strong decrease, moderate decrease, no change, moderate increase, strong increase.

x	Med$_t$	Med$_p$	WRST[a]	$P(x\|Regime = 0) > P(x\|Regime = 1)$[b]
Investment in CO_2 abatement technology	moderate increase	moderate increase	0.0000***	26.9 %
Other investments	no change	no change	0.5055	47.3 %
R&D expenditures in CO_2 abatement technologies	no change	no change	0.9100	50.5 %
Other R&D expenditures	no change	no change	0.6898	48.7 %

[a] p value of the Wilcoxon rank-sum test with significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
[b] Probability that x from a random draw of the group of taxpaying firms ($Regime = 0$) is larger than from a random draw of the group of permit trading firms ($Regime = 1$).

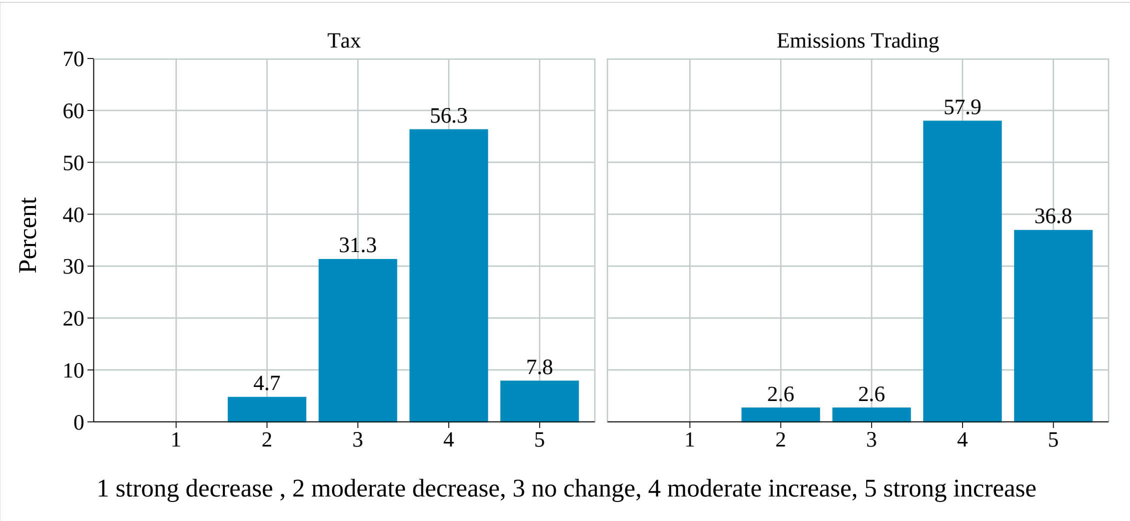

Figure III.2: Effects of climate policy on investments in CO_2 abatement technologies; observations in subsamples: $N_t = 64$, $N_p = 38$.

The median confirms a moderate increase in investments in CO_2 abatement technologies for both groups of firms. This result indicates that both measures – the tax and permit trading – stimulate firms' willingness to invest into abatement technologies due to policy implementation. However, for the permit trading group the policy impact is stronger than for the tax paying group: While 94.7 percent of trading firms report a moderate or strong increase in their investments, the value of tax-paying firms is only 64.1 percent. The Wilcoxon rank-sum test therefore gives a statistically significant difference in the distribution of the two groups with a probability of 73.1 percent that permit trading firms appear with a higher value on the response scale of this question.

With respect to abatement technology adoption and innovation issues, interesting conclusions can be drawn from data generated by three more questionnaire items concerning the effects of climate policy implementation (see Table III.2). First, changes in all investment expenditures were addressed, except those for abatement technologies. Although investment in CO_2 abatement technologies increased moderately for the median firm in both subsamples, investment expenditures for all other business activities remained unchanged. Consequently, we might conclude that firms make CO_2-related investments additionally and that there are no crowding-out effects. A second and third conclusion resulted from the consideration of R&D expenditures: The median firm is unaffected by climate policy in its R&D expenditures on CO_2 abatement technologies and in its R&D expenditures of all the other businesses. The analysis results of all three items share one thing in common: There is no significant difference between the instrument groups.

The results from the bivariate analysis are a good indicator that differences do exist in the technology adoption behavior of firms conditional on the policy instrument with which they are regulated. Permit trading seems to dominate the tax in providing incentives to adopt abatement technologies. It should be kept in mind, however, that firms self-select their preferred instrument. It is reasonable to assume that firms choose the instruments according to their specific attributes, so that instrument affiliations are not random. This fact has to be taken into account before drawing any conclusions on abatement technology adoption behavior under different regulatory regimes. Therefore, multivariate analysis allowing for endogenous instrument choice is required to draw inferences on causal relationship between the use of different regulatory regimes and the technology adoption behavior of firms. The results of this analysis and the econometric methods employed are presented in the next section.

III.6 Results from a Multivariate Analysis

Research on technological change usually requires a dynamic approach with the empirical analysis based on panel data. Our data sample, however, comprises only a snapshot in time, i.e. cross-sectional data for the year 2008. Firms were asked to report data regarding their expenditures on CO_2 abatement technologies for three time periods, but with varying time horizons. Due to these data limitations, we follow an alternative approach to determine the differential effects that different environmental policy regimes may have on technology adoption. Therefore, we use the investment intensity of the first year in which climate policy instruments were implemented ($Invest_{08}$) as our outcome of interest and make it dependent on historic expenditures ($Invest_{hist}$) as a proxy for a firm's stock of abatement technologies prior to climate policy implementation. A firm's instrument choice between the tax and permit trading (*Regime*) is then the dummy regressor of primary interest.

Estimating the regime-dependent effects on technology adoption with our Swiss firm data is not straightforward. The difficulty in estimation basically arises from two data characteristics, but also from small sample size.

First, a significant proportion of firms exhibit zero investment expenditures, while the other firms display positive levels of expenditure. Thus, our dependent variable is left-censored with a masspoint at zero.

Second, as the Swiss Confederation allows firms to choose between instruments, it is natural to assume that firms' choices are not random. From the set of instruments, they choose the one under which they expect lower costs. As analyzed by Oberauner (2010), instrument choices are driven by firms' emissions intensities, their wage intensities and their abatement efforts. So, firms make their decisions according to their specific characteristics and attributes. Thus, it is reasonable to assume that firms' decisions on investment expenditures are not independent of their decisions for one of the instruments (self-selection bias).

Finally, the small sample size restricts the number of regressors used and even rules out the use of some statistical methods.[11]

These concerns, the censored nature of investment expenditures, the endogeneity

[11]Calculating average treatment effects with permit trading firms in the treatment group and taxpaying firms in the control group failed in the construction of a convincing counterfactual due to small sample size. Furthermore, using a two-step procedure for the left-censored dependent variable results in the estimation's collapse.

problem of the explanatory variable *Regime*, and the limited applicability of statistical methods make the econometric analysis a challenging task. Given these peculiarities, a simultaneous two-equation model with one equation being a Tobit-type to account for censoring of the dependent variable $Invest_{08}$, and the other equation being a Probit-type to estimate *Regime*, appeared to be the most appropriate method with which to approach our research question. Firms' instrument choices are modeled in line with Oberauner (2010) except for using a Probit rather than a Logit model.[12] We allow the two equations to be correlated in their error terms in order to address the assumption of endogeneity of *Regime*. The decisions of firms and the respective empirical models are illustrated in Figure III.3 in Appendix III.A.2.

The formal exposition of the simultaneous Tobit-Probit model (STP) is given by Eq. (III.1) to Eq. (III.5).[13] The first equation characterizes the outcome of interest y_1 (i.e. $Invest_{08}$). The second equation models firms' choices of instrument y_2 (i.e. *Regime*). Both equations formalize limited dependent variables, thus requiring latent variable notation.

$$y_{1i}^{*} = \alpha y_{2i} + \beta_1 X_{1i} + \varepsilon_{1i} \tag{III.1}$$

$$y_{2i}^{*} = \beta_2 X_{2i} + \varepsilon_{2i} \tag{III.2}$$

$$y_{1i} = \begin{cases} y_{1i}^{*} & \text{if } y_{1i}^{*} > 0 \\ 0 & \text{if } y_{1i}^{*} \leq 0 \end{cases} \tag{III.3}$$

$$y_{2i} = \begin{cases} 1 & \text{if } y_{2i}^{*} > 0 \\ 0 & \text{if } y_{2i}^{*} \leq 0 \end{cases} \tag{III.4}$$

$$\mathcal{E}\left(\varepsilon_{ji}\right) = 0; \quad \mathcal{E}\left(\varepsilon_{ji}\right)^2 = 1; \quad \mathcal{E}\left(\varepsilon_{1i}\varepsilon_{2i}\right) = \rho \tag{III.5}$$

for $j = 1, 2$ and $i = 1, \ldots, n$

y_{ji}^{*} refers to the latent variables and indicates firms' propensities to invest in abatement technologies and their propensities to choose emissions trading, respectively.

[12]For the estimation of the Tobit-Probit model, we used the user-written Stata command *cmp* that does not provide Logit estimation. Given the identical sample of firms and the model conversion factor of Amemiya (1981), model choice has only a negligible impact on the coefficients estimated.

[13]For ease of exposition, we use the generic notation y and x to refer to the outcome variables and the regressors, respectively.

y_{ji} denotes the observed variables with y_{1i} being left-censored and y_{2i} being binary, α is a scalar coefficient, β_j the vectors of coefficients, X_{ji} the vectors of regressors, and ε_{ji} the error terms. The expected values of the error terms are zero; the variances are one. Furthermore, the error terms are assumed to have a bivariate normal distribution with a correlation coefficient ρ measuring the endogeneity of y_2 in Eq. (III.1).

X_{1i} comprises the variables $Invest_{hist}$, i.e. the proxy for the stock of abatement technologies, and the dummy variables $Abate_{mod}$ and $Abate_{high}$ in order to control for firms' abatement levels. Alternative specifications of our empirical model were estimated including the variables $Invest_{fut}$, $Emissions$ and the log-transformed sales in 2008. However, based on a Likelihood-ratio test, no statistically significant influence of these variables on $Invest_{08}$ could be observed. Hence, to keep the number of regressors small, these variables were not further considered in our analysis when investment intensities served as the dependent variable. Following Oberauner (2010), X_{2i} consists of the regressors $Emissions$, $Wages$, and again the abatement dummies.

The STP model was estimated using the user-written STATA command *cmp* (conditional mixed-process estimator; Roodman, 2010). The STP results are compared to single equation estimations of Eq. (III.1) and Eq. (III.2), i.e. for the case in which $\rho = 0$ with firms' instrument choices and their investment decisions treated as being independent of each other. Moreover, we ran a simple OLS regression for Eq. (III.1) for the purpose of comparison.[14] The estimated coefficients of the various models are presented in Table III.3, the marginal effects for the Tobit and the STP model in Table III.4, and the summary statistics of the variables in Table III.6 in Appendix III.A.3.

Table III.4 shows the latent variable and unconditional marginal effects for the Tobit and the STP coefficients, holding all other variables constant at their mean values. The latent variable marginal effects measure changes in the mean of y^* and equal the estimated coefficients when the regressors are continuous ($\beta = \partial\mathcal{E}\left(y^*\right)/\partial x$); the unconditional marginal effects denote the changes in the censored mean of the observed investment intensities in 2008 ($\partial\mathcal{E}\left(y\right)/\partial x$). The marginal effects of the dummy variables were calculated as the discrete changes, e.g. the censored mean of $Invest_{08}$

[14]For censored data, OLS estimation is biased and not consistent. The linear regression model ignores the cluster of zeros of the dependent variable and that y_1 cannot be negative. The higher the share of zeros, the greater is the discrepancy between the Tobit and the OLS results. Furthermore, constant marginal effects are unrealistic when a considerable share of the dependent variable has a value of zero (Winkelmann and Boes, 2006).

$(\mathcal{E}(y|x))$ increases by 0.0091 when *Regime* turns from 0 to 1, i.e. from the tax to the permit trading regime.

Table III.3: Estimation results for the intensity of investments in CO_2 abatement technologies with the investment intensities modeled in levels.

	OLS	**Probit**	**Tobit**	**STP**
Regime	0.0054		0.0133*	0.0250***
	(1.2221)		(1.9152)	(3.0085)
$Invest_{hist}$	0.3780***		0.4119***	0.3857***
	(5.5371)		(4.0775)	(4.1526)
$Abate_{mod}$	−0.0039		0.0186*	0.0146
	(−0.8426)		(1.8211)	(1.4107)
$Abate_{high}$	0.0029		0.0302***	0.0265**
	(0.5796)		(2.8717)	(2.4848)
Constant	−0.0010		−0.0367***	−0.0391***
	(−0.3742)		(−4.1496)	(−4.1302)
Emissions		0.0678***		0.0651***
		(3.5957)		(3.4855)
Wages		−15.5659***		−13.6494***
		(−2.9279)		(−2.7999)
$Abate_{mod}$		2.5613**		2.7244**
		(2.3543)		(2.5110)
$Abate_{high}$		2.9185**		2.9587***
		(2.5048)		(2.6065)
Constant		−0.8561		−1.3131
		(−0.6979)		(−1.1432)
σ			0.0220***	0.0223***
ρ				−0.7647**
N	84	72	84	88
N cens.			44	44
N uncens.			40	40
R^2	0.3923			
Adj. R^2	0.3616			
Pseudo R^2		0.6312		
R^2_{MZ}			0.5357	0.5628

t or z statistics in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The marginal effects of the abatement dummies require thorough consideration. The marginal effect of $Abate_{mod}$ measures the increase in the investment intensity when abatement is raised from a low to a moderate level ($Abate_{high} = 0$). The marginal effect of $Abate_{high}$ coherently depicts the effect when moderate abatement turns to high abatement ($Abate_{low} = 0$).[15]

For the STP model, the coefficients of *Regime* and $Invest_{hist}$ exhibit positive signs and are significantly different from zero at the 1 percent level. With regard to the abatement dummies, a statistically significant influence can only be observed when abatement is at a high level.

Table III.4: Latent variable and unconditional marginal effects for Tobit and STP regressions in levels with discrete changes of the dummy variables.

	$\mathbf{ME_{Tobit}}$		$\mathbf{ME_{STP}}$	
	$\mathcal{E}(y^*\|x)$	$\mathcal{E}(y\|x)$	$\mathcal{E}(y^*\|x)$	$\mathcal{E}(y\|x)$
Regime	0.0133	0.0046	0.0250	0.0091
$Invest_{hist}$	0.4119	0.1268	0.3857	0.1149
$Abate_{mod}$	0.0186	0.0043	0.0146	0.0033
$Abate_{high}$	0.0116	0.0055	0.0119	0.0051

Due to a high share of censored observations in our sample (about 52 percent), OLS estimates deviate considerably from the Tobit and the STP estimates. Furthermore, the STP model shows up with a statistically significant correlation between the error terms, i.e. from a statistical point of view, firms' decisions on how much money to spend on advanced abatement technologies actually depend upon their instrument decisions.

Goodness of fit measures – expressed by McFadden's R^2 for the OLS regression and by McKelvey and Zavoia's R^2 for the Tobit and the STP regression – indicate a high predictive power of the STP model compared to OLS, and even a considerable improvement compared to the single Tobit estimation.[16]

In addition to the results in Table III.3 with the investment intensities in levels, we ran regressions with the intensities transformed to logs. The results are presented in

[15] Typically, standard commands of statistical software produce discrete-change effects for dummies when they turn from 0 to 1, holding all other regressors at their mean values. For categorical variables, erroneous results were generated with these commands by treating the residual category dummies as standalone regressors. Calculating the discrete effects from low to high abatement or from low to moderate and moderate to high abatement generate correct results. We chose the more plausible second alternative.

[16] In a Tobit model, McFadden's pseudo R^2 is meaningless as the dependent variable is continuous but limited and can therefore take values that are either positive or negative (Cameron and

Table III.7 in Appendix III.A.4. For both, estimations in levels and logs, we observe the following qualitatively robust effects.

First, in promoting the adoption of advanced abatement technologies, tradable permits dominate the tax. Our empirical analysis thereby contradicts the traditional theoretical literature argument (brought forward, e.g. by Milliman and Prince, 1989 and Jung et al., 1996) that a tax provides stronger incentives than free permits.

This result is unexpected, not simply because it is the exact opposite of what the theoretical literature predicts, but also because compelling reasons are observed in practice that would further indicate that taxes provide higher adoption incentives. The current tax rate is comparatively high (36 CHF). Although, the tax rate was only 12 CHF in 2008, national emission reductions were expected to be low and consequently the tax rate was expected to be raised sooner or later by the Swiss Confederation. Moreover, a trading platform for permits did not evolve. So, the emissions trading scheme was unable to deliver a reliable price signal for permits. In addition, trade volumes were negligible in 2008 (Swiss Federal Office for the Environment, 2008). On the one hand, this is due to the missing trading platform, but first and foremost due to the overallocation with permits.[17] Based on these aspects, the observed relative stringency appears to be higher under the tax regime. Thus, we would presume higher technology adoption under the tax regime due to higher compliance costs.

As shown by Requate and Unold (2003), underinvestment under a tax might occur if the regulator anticipates the new technology before firms adopt. This might not have happened in Switzerland when policy measures were designed. Swiss climate policy is the result of a long political compromise that did not fully account for efficiency criteria and policy-induced technological progress.

However, uncertainty may be a plausible reason for our empirical findings. In prac-

Windmeijer, 1997). Therefore, we report McKelvey and Zavoina's R^2

$$R^2_{MZ} = \frac{\sum_{i=1}^{N} (\hat{y}_i^* - \bar{y}^*)^2}{\sum_{i=1}^{N} (\hat{y}_i^* - \bar{y}^*)^2 + N\hat{\sigma}^2},$$

as proposed by Veall and Zimmermann (1996). The authors claim that this measure provides the best possible comparability across an OLS and a Tobit model.

[17] Comparing the national allocation plan with the actual emissions in 2008 leads to this conclusion (Swiss Federal Office for the Environment, n.d.a and Swiss Federal Office for the Environment, n.d.b).

tice, abatement costs are exposed to considerable volatility (e.g. shocks in input prices or output demand) that influence the investment strategies of firms. Usually, firms regulated by a tax know whether their potential abatement technology investment is profitable once the tax rate is announced. In contrast, the volatile permit price impairs a firm's planing security. As analyzed by Insley (2003), firms delay their investment decisions in a system of tradeable permits since uncertainty raises the option value of the investment. The author points out that once the new technology is installed, the option to invest is forgone and consequently the option to alternatively buy allowances when the future permit price is low. In our Swiss data, we cannot observe permit trading to be delayed compared to the tax; the opposite seems plausible and may be due to late policy announcement in June 2007.[18] Investment expenditures are typically planed at least over the medium term. So, firms' adaptive behavior to climate policy implementation may not be fully reflected in the 2008 investment expenditure data. There is also the fact that a number of trading firms voluntarily engaged in emission reductions within the framework of the EnAW (see Footnote 9) prior to policy implementation, i.e. they might have started to invest in abatement technologies before any mandatory measures were in place. So, transition effects may be less prevalent with trading firms than with firms under the tax regime.

In contrast to Insley (2003), Zhao (2003) argues that both, firms under a tax and firms under tradeable permits, are affected by uncertainty as – in an efficient permit market – price volatility stems from abatement cost uncertainty, which reduces planing security under both regimes. In this context, a system of tradeable permits is the preferred instrument. Moreover, as the Swiss Confederation raises the tax rate when national annual emissions targets are not achieved (see Footnote 3), an additional uncertainty dimension is added to the tax regime. However, it has to be noted that the uncertainty argument may not tell the whole story. The effect of uncertainty in firms' decision behaviors might be overestimated. As shown by Oberauner (2010), even already in firms' instrument choices, uncertainty has no significant impact.

Besides transition effects and uncertainty, it may be reasonable that the perceived policy stringency is responsible for the dominance of free permits in providing incentives for technology adoption. The tax is included in the fossil fuel invoice amount and represents only a small percentage of fossil fuel costs (about 3 Rappen per liter of heating oil). Moreover, the volatility of fossil fuel prices makes the tax even less

[18]The policy was announced by the end of June 2007 and implemented by January 2008 (Swiss Federal Office for the Environment, 2007).

apparent. Within the emissions trading regime, firms commit to reduction targets and define reduction measures together with the EnAW, who continually monitors firms' compliance progress. A firm's management and its affected workforce may feel more committed in complying with the policy and may develop a growing awareness of environmental and climate protection issues. This could possibly lead them to invest without delays. Thus, although there is no price signal for tradeable permits, firms may perceive a more stringent regulation in the permit regime compared to the tax.

Second, besides *Regime*, the results of Tables III.3 and III.4 as well as Table III.7 in Appendix III.A.4 indicate that the investment decisions of firms are further influenced by their historic investment expenditures, which can be treated as their stock of abatement technologies. Firms' investment expenditures increase with their pre-policy expenditures for abatement technologies. The positive stock effect is, however, the opposite of what Kerr and Newell (2003) found for the U.S. lead phasedown, where previously adopted technology had a negative effect on current adoption. As we do not have investment intensity data for the year 2007, we are not able to infer implications about the effect of policy implementation on technology adoption itself.

Third, firms' overall abatement activities play a double role in our empirical model. On the one hand, firms are more likely to participate in emissions trading rather than pay a tax when they act at a higher abatement level – a result derived by Oberauner (2010). On the other hand, given instrument choice, high abatement encourages firms to increase their investments in abatement technologies. Our results indicate a monotonic increase in investment intensities when abatement rises. This is a convincing result, since increases in abatement typically arise from cost-reducing new abatement technologies.

Finally, as already mentioned above, empirical evidence cannot be provided with respect to sales in 2008, $Invest_{fut}$, and $Emissions$. Regarding sales, we would expect that firm size enhances investment expenditures due to, for example, scale economies or better access to financial resources as empirically put forward, for example, by Kerr and Newell (2003). The fact that we cannot observe a significant influence of future investment plans is surprising, as our results also indicate a robust positive stock effect for the transition from the pre-policy period to our first period of regulation (2008). We would expect that firms' intentions to adopt new technologies in future affect their decisions today. With regard to $Emissions$, we observe statistical significance with the abatement dummies, which are a better indicator for expressing the environmental impacts anyway.

While these results are a good first indicator on the instrument-related effects, we have to admit three major concerns with our approach which need to be addressed by future research.

First of all, econometric model assumptions are violated. In general, a Tobit estimation depends crucially on the assumptions of normal error terms and homoskedasticity, which is a serious issue with regard to our results in Table III.3. A Lagrange multiplier test indicates a strong rejection of the normality and homoskedasticity hypotheses. As investment intensities in 2008 are heavily skewed and have a considerable non-normal kurtosis, it was reasonable to run the regressions with log-transformed intensity data (i.e. $lnInvest_{08}$ and $lnInvest_{hist}$).[19] The analogue of Table III.3 with the log-transformed data are presented in Table III.7 in Appendix III.A.4. Yet, log-transformation did not solve the problem. Again, the estimations failed to provide normality and homoskedasticity of the predicted error terms. Furthermore, retransformation problems arose in this context that are discussed in further detail in Appendix III.A.4. With the normality and homoskedasticity assumptions violated, caution in the interpretation and the communication of our results is required. Nevertheless, we observe qualitatively similar economic effects for almost all models estimated and for the dependent variable modeled in levels and logs, respectively.

Second, a larger sample size is necessary in two respects. On the one hand, a larger cross-section would be desirable to improve the applicability of other econometric techniques that are potentially better suited to the problem and to increase the representability and the validity of the results. On the other hand, evaluating our research question with panel data is a more appropriate approach for identifying the dynamic effects of technological change.

Finally, to measure the regime-dependency of technology adoption, we used investment expenditure data of 2008, i.e. data of the first year in which climate policy measures were established. Historic investment (i.e. prior to policy implementation) served as one of the regressors to control for the policy-independent stock of abatement technologies. Future investment (2009/2010) was omitted from the regression models as no statistically significant influence was to be observed. The fact that only one data point in time was used, and specifically the first year of policy implementation, may be problematic as there may be transition effects from a non-regulatory period to a period of regulation.

[19] See Table III.5 and Footnote 8 for the different scaling of $Invest_{08}$ and $lnInvest_{08}$, respectively.

These issues indicate that standardized and periodical surveys with mandatory firm participation are required to provide a solid and representative data pool for the analysis of this research question. One has to keep in mind, however, that the outstanding economic conditions provided by Swiss climate policy might not continue indefinitely to provide a paradise for empirical research on prices vs. quantities. Climate policy design in Switzerland may change for the post-Kyoto period, and the unique conditions may be destroyed, e.g. the revised CO_2 Act for the post-Kyoto climate stipulates compulsory participation in permit trading for emission-intensive firms (Swiss Federal Assembly, 2011).

From the bivariate and the multivariate analysis, we can draw one general conclusion: Although our firm sample is small and there are statistical weaknesses, the methods used consistently indicate that there are stronger incentives for technology adoption under free permits. While the bivariate analysis gives a first indication on the direction of this effect, the multivariate analysis confirms evidence that tradeable permits may be superior in promoting technology adoption in practice.

III.7 Conclusions

To our knowledge, this study is the first contribution to the empirical literature on the differential impacts of an emissions tax and a system of tradeable permits in promoting advanced abatement technology adoption. The unique design of climate policy in Switzerland, with both instruments implemented simultaneously, allows us to investigate the incentives that both regimes may induce in this context. The Swiss Confederation usually lets energy-intensive firms choose among a tax and tradeable permits to regulate carbon dioxide emissions. Thus, based on Swiss firm data, the differential impacts of the instruments could be analyzed with all other economic conditions being equal.

The conclusions of our empirical study can be drawn from the results of both, a bivariate and a multivariate analysis. In the bivariate analysis, we compare the intensities of abatement technology investments of permit trading firms with those of firms that pay an emissions tax for three time periods: (1) prior to climate policy implementation, (2) in the year of implementation, i.e. 2008, and (3) a forward-looking period 2009/2010. In all three periods, investments in CO_2 abatement technologies are dominated by emissions trading firms, independent of policy implementation. Besides, firms under both regimes report a moderate increase in abatement technology investments since the policy measures were introduced. However, this effect is stronger for firms under tradeable permits.

Our multivariate analysis comes to a similar conclusion: Compared to the tax, emissions trading seems to provide stronger incentives for firms to adopt advanced abatement technologies. Our analysis is based on the assumption that a firm's decision between the tax and permit trading (a variable that is binary) is not independent of a firm's decision on how much money it invests in advanced CO_2 abatement technologies (a variable that is censored from the left at zero). We approach a simultaneous Tobit-Probit model to account for this endogeneity problem.

Besides the influence of the instrument, pre-policy investments drive a firm's expenditures for abatement technologies. The more money a firm spends prior to policy implementation, the more likely is the firm to invest once the regulation is in place. So, a stock effect is observed that reflects the dynamics of investments. Moreover, but with limited statistical evidence, firms' abatement levels influence their decisions on how much money to spend on CO_2 abatement technologies. No evidence can be brought forward, however, with regard to firms' sales, their future investments in CO_2 abatement technologies, and their emissions intensities.

Admittedly, the multivariate analysis suffers from the small sample size and, moreover, the crucial econometric model assumptions are violated. In spite of these weaknesses, the study provides insights into the main drivers of firms' investment expenditures on abatement technologies under different regulatory regimes in practice. Besides, our current study yields a qualitatively robust result, regardless of the statistical method used to analyze the best available data: Tradeable permits dominate the tax in promoting the adoption of advanced abatement technologies. Thus, our findings stand in direct opposition to the traditional theoretical result according to which the tax is superior with regard to enhancing dynamic efficiency. Abatement cost uncertainties, transition effects in adapting to policy implementation, and a differing perception of instrument stringency might explain why we observe significantly higher investment expenditures in abatement technologies for firms under a system of tradeable permits.

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III.A Appendix

III.A.1 Variables Used in the Empirical Analysis

Table III.5: List of variables.

Variable	**Label**
$Invest_{hist}$	Intensity of abatement technology investments prior to climate policy implementation in 2008, i.e. investment expenditures prior to 2008 [Swiss francs] divided by sales in 2008 [Swiss francs]
$lnInvest_{hist}$	Natural logarithm of intensity of abatement technology investments prior to climate policy implementation in 2008, i.e. investment expenditures prior to 2008 [Swiss francs] divided by sales in 2008 [million Swiss francs]
$Invest_{08}$	Intensity of abatement technology investments in the first year of climate policy implementation (2008), i.e. investment expenditures in 2008 [Swiss francs] divided by sales in 2008 [Swiss francs]
$lnInvest_{08}$	Natural logarithm of intensity of abatement technology investments in the first year of climate policy implementation (2008), i.e. investment expenditures in 2008 [Swiss francs] divided by sales in 2008 [million Swiss francs]
$Invest_{fut}$	Intensity of abatement technology investments in 2009 and 2010, i.e. investment expenditures in 2009/2010 [Swiss francs] divided by sales in 2008 [Swiss francs]
$Regime$	Dummy variable indicating a firm's instrument choice, i.e. the regulatory regime to which it is affiliated (1=emissions trading, 0=tax)
$Abate\_low$	Dummy variable indicating low overall abatement in 2008 (less than 5 %) – reference dummy
$Abate\_mod$	Dummy variable indicating moderate overall abatement in 2008 (5 – 19 %)
$Abate\_high$	Dummy variable indicating high overall abatement in 2008 (20 % or more)
$Emissions$	Carbon emissions intensity (i.e. CO_2 emissions in 2008 [tonnes of CO_2] divided by sales in 2008 [million Swiss francs]) as a proxy for potential permit allocation
$Wages$	Wage intensity (i.e. gross wages in 2008 [Swiss francs] divided by sales in 2008 [Swiss francs]) to indicate the potential refund of tax receipts

III.A.2 Firms' Choices and Econometric Models

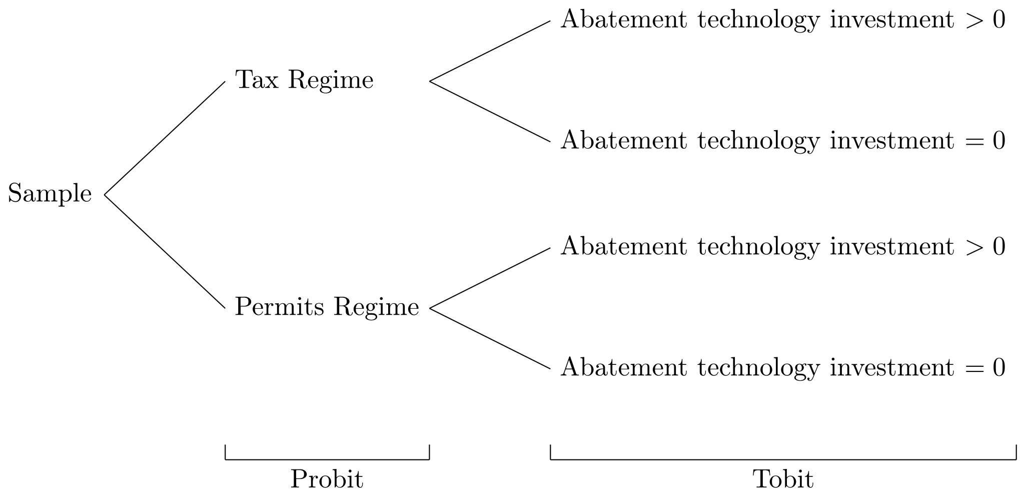

Figure III.3: Firms' choices and econometric models.

III.A.3 Summary Statistics of Variables Used in the Multivariate Analysis

Table III.6: Summary statistics for the Tobit model in levels and logs and for the Probit model.

	Obs.	Mean	Med.	Std.Dev.	Min	Max
$y_1 = Invest_{08}$						
$Invest_{08}$	84	0.0058	0	0.0195	0	0.1481
$Regime$	84	0.3452	0	0.4783	0	1
$Invest_{hist}$	84	0.0146	0.0018	0.0276	0	0.1111
$Abate_{mod}$	84	0.3452	0	0.4783	0	1
$Abate_{high}$	84	0.2857	0	0.4545	0	1
$lny_1 = lnInvest_{08}$						
$lnInvest_{08}$	84	3.7548	0	4.1600	0	11.9060
$Regime$	84	0.3452	0	0.4783	0	1
$lnInvest_{hist}$	84	5.3505	7.4825	4.7054	0	11.6183
$Abate_{mod}$	84	0.3452	0	0.4783	0	1
$Abate_{high}$	84	0.2857	0	0.4545	0	1
$y_2 = Regime$						
$Regime$	72	0.4167	0	0.4965	0	1
$Emissions$	72	33.6314	8.2227	56.0712	0.0148	287.6916
$Wages$	72	0.2399	0.2094	0.1274	0.0079	0.7295
$Abate_{mod}$	72	0.4167	0	0.4965	0	1
$Abate_{high}$	72	0.3056	0	0.4639	0	1

III.A.4 Multivariate Analysis in Logs

Table III.7: Estimation results for the intensity of investments in CO_2 abatement technologies with the investment intensities modeled in logs.

	OLS	**Probit**	**Tobit**	**STP**
Regime	3.2763***		4.0887***	5.1808***
	(4.3336)		(3.1591)	(3.0273)
$lnInvest_{hist}$	0.2932***		0.5533***	0.5116***
	(3.8523)		(3.5746)	(3.2416)
$Abate_{mod}$	1.4672*		4.9848**	4.7007**
	(1.7351)		(2.6139)	(2.4547)
$Abate_{high}$	2.4849***		6.6406***	6.3454***
	(2.7284)		(3.3796)	(3.2214)
Constant	−0.1615		−7.2016***	−7.2142***
	(−0.3200)		(−4.0456)	(−4.0417)
Emissions		0.0678***		0.0645***
		(3.5957)		(3.3894)
Wages		−15.5659***		−15.1677***
		(−2.9279)		(−2.9156)
$Abate_{mod}$		2.5613**		2.5822**
		(2.3543)		(2.4920)
$Abate_{high}$		2.9185**		2.8942***
		(2.5048)		(2.6043)
Constant		−0.8561		−0.8457
		(−0.6979)		(−0.7383)
σ			4.3156***	4.3515***
ρ				−0.3731
N	84	72	84	88
N cens.			44	44
N uncens.			40	40
R^2	0.6059			
Adj. R^2	0.5860			
Pseudo R^2		0.6312		
R^2_{MZ}			0.6659	0.6717

t or z statistics in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table III.7 shows the results of the multivariate analysis with the log-transformed investment intensities analogue to the level results in Table III.3. Significance values and model fit considerably improved compared to level regressions. Furthermore, the coefficients exhibit the same directions as for the Tobit and the STP estimations in levels. However, we cannot provide statistical evidence with respect to our assumption of correlated error terms between the Tobit and the Probit equation.

Models using the log-transformation of the dependent variable raise retransformation concerns, since the values of the predicted mean and the marginal effects are not simply obtained by taking their exponential ($exp(\mathcal{E}\,(ln\ y)) \neq \mathcal{E}\,(y)$; Cameron and Trivedi, 2009). Retransformation requires an adjustment factor that is dependent on the estimated variance. Cameron and Trivedi (2009) emphasize the high sensitivity of the retransformed results on estimates of σ that are biased when errors are non-normal and heteroskedastic. According to the results of a Lagrange multiplier test, the normality and homoskedasticity assumptions are violated even for the models in logs. As a consequence, retransformation leads to exorbitantly high and unrealistic mean values of our dependent variable. Therefore, we abstain from reporting any marginal effects for the log-models.

Curriculum Vitae

Iris Maria Oberauner was born on May 8, 1977 in Mondsee (Austria) as the third child of Maria Theresia and Anton Walter Oberauner (residing in Innerschwand am Mondsee in Austria). From 1983 to 1987 she attended the elementary school in Innerschwand am Mondsee (Austria). She then visited the secondary school in Mondsee until 1991. She subsequently attended the Bundeshandelsakademie in Neumarkt am Wallersee (Austria) and successfully passed her Matura in 1996.

She enrolled to study Business Administration at the University of Innsbruck (Austria) in 1997, and in 2003 she additionally took up studies in Economics. She wrote her diploma thesis in the field of Environmental Economics. In 2005, she graduated in both studies, receiving her double "Magistra für Sozial- und Wirtschaftswissenschaften" (corresponding to a Master's degree). From 1993 to 2005, she held several part-time and temporary positions as an office employee and later at the University of Innsbruck.

After her studies, she worked at two research institutes (Joanneum Research and Wegener Center for Climate and Global Change, both in Graz, Austria) and as an external lecturer in the field of International Economics at the University of Innsbruck at the same time.

In 2007, she moved to Basel to take up an appointment as a teaching and research assistant for Prof. Dr. Frank C. Krysiak at the Faculty of Business and Economics of the University of Basel. During this assignment, Iris wrote her doctoral thesis in the field of Environmental Economics, which she completed in May 2012. She also attended various summer schools and presented her academic work at several international conferences while writing her thesis.

Currently, Iris works at the Swiss Federal Office for the Environment in Ittigen (Canton of Bern) as an economist.