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INDUSTRY COMPENSATION UNDER RELOCATION RISK: A FIRM-LEVEL ANALYSIS OF THE EU EMISSIONS TRADING SCHEME[*]

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Abstract

When regulated firms are offered compensation to prevent them from relocating, efficiency requires that payments be distributed across firms so as to equalize *marginal* relocation probabilities, weighted by the damage caused by relocation. We formalize this fundamental economic logic and apply it to analyzing compensation rules proposed under the EU Emissions Trading Scheme, where emission permits are allocated free of charge to carbon intensive and trade exposed industries. We show that this practice results in substantial overcompensation for given carbon leakage risk. Efficient permit allocation reduces the aggregate risk of job loss by more than half without increasing aggregate compensation.

Keywords: Industry compensation, industrial relocation, emissions trading, permit allocation, EU ETS, firm data

JEL Classifications: H23, H25, Q52, Q54, F18

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1 Introduction

Government intervention in the marketplace is often justified as a means to increase net social welfare. When imposing welfare-improving regulation, a benevolent government may be able to tax part of the welfare gains and use the revenue to compensate industry for the cost of compliance. But when should compensation be offered, to whom, and how much? Should firms that pollute the environment be offered compensation for the cost impact of a regulation that forces them to internalize the environmental damage? Should financial institutions be offered compensation for a tax levied on financial transactions?

The distributional effects of regulation have far-reaching consequences for policy design. If no compensation is offered, industry has incentives to spend large amounts on raising political support against the policy, and to lobby for exemption clauses that weaken the policy's effectiveness. Worse, when the policy is not harmonized across jurisdictions, firms may find it profitable to relocate to an unregulated one. As the head of a leading financial transactions company recently told the BBC: "If [the financial transaction tax] really happened, we would have to move our business to New York or Singapore or Hong Kong. Our business would continue. [It is] just sad it wouldn't continue in London."[1] The threat of relocation – if credible – is a powerful argument to extract concessions from politicians of all stripes, as regulation-induced job losses are likely to cloud their re-election prospects.

In the realm of climate policy, the threat of relocation is aggravated by "carbon leakage", i.e. the phenomenon that industrial relocation shifts greenhouse gas (GHG) emissions to places beyond the regulator's reach. Since GHG emissions are a global public bad, relocation not only costs jobs at home but also weakens the environmental effectiveness of the policy. It is therefore not surprising that generous compensations are pervasive in this area.[2] For example, numerous European

[1] BBC interview with Michael Spencer, Group Chief Executive Officer of ICAP, available online at http://www.bbc.co.uk/news/business-16990025.

[2] The evidence on whether the threat of relocation is credible is very scant when it comes to climate policy. Martin, de Preux, and Wagner (2011) find no evidence that the UK Climate Change Levy caused output reductions or plant exit among treated firms. The literature on foreign direct investment and more broadly-defined environmental regulation suggests that, in some industries, lo-

countries have implemented carbon taxes since the 1990's, and virtually all of them grant rebates or exemptions to energy-intensive firms, even though this practice runs counter to the polluter-pays principle underlying environmental policy-making in the EU.

This paper puts forth the simple but so far little appreciated economic logic that compensation should be offered first to those firms where it leads to the highest marginal improvement of the government's objective function associated with the policy. This is different from compensating the firms with the highest propensity to relocate. Rather, an efficient compensation rule equalizes across firms the *marginal* propensity to relocate, weighted by how damaging their relocation is to the government's objectives.

We analyze the implications of this idea in the context of industry compensation rules established under the European Union Emissions Trading System (EU ETS), the largest cap-and-trade system worldwide. The EU ETS imposes an overall cap on CO_2 emissions from stationary sources – mostly power stations and industrial plants – in 31 countries.[3] Emitters with heterogeneous abatement costs can trade permits amongst each other or with third parties so as to lower their total abatement cost and hence, the total cost of complying with the cap on CO_2. Since the beginning of the EU ETS in 2005, industrial emitters have been compensated for the cost of compliance by receiving fairly generous allocations of free permits based on their past CO_2 emissions. Contrary to its initial plan of phasing in auctioning of permits from 2013, the European Commission (EC) has decided in 2009 that free permit allocation will be continued for industries deemed at a heightened risk of carbon leakage. Determining which industries are at risk is complicated by asymmetric information about compliance costs. Regulated firms face an incentive to

cation choice is indeed deterred by environmental regulatory stringency (e.g. Wagner and Timmins, 2009; Hanna, 2010).

[3]Participation in the EU ETS is mandatory for firms with installations that specialize in an energy-intensive activity and whose capacity exceeds specific thresholds. As established by the EU Emissions Trading Directive 2003/87/EC, the principal regulated industries in phases I and II of the EU ETS have been fossil-fuel fired power plants and other large combustion installations, oil refineries, coke ovens, ferrous metals, minerals, and pulp and paper. The interested reader is referred to the book by Ellerman, Convery, and de Perthuis (2010) for a comprehensive review and in-depth economic analysis of this policy.

exaggerate these costs in order to extract more rents in the form of free permits, or to lobby for a more lenient overall cap. The EC decided to exempt from permit auctions industries that are either very carbon intensive or very trade exposed, or that exceed certain threshold values on both measures. There is, however, no empirical evidence that these exemption criteria are in any way related to actual relocation or downsizing risk, let alone the marginal impacts of compensation on such risk.

This paper provides the first evidence on this topic based on new firm-level data we gathered in telephone interviews with managers of 761 manufacturing firms in six European countries. We applied a new survey tool developed recently by Bloom and van Reenen (2007) with the objective to mitigate known types of bias arising in conventional survey formats. The method allows us to elicit information on politically contentious issues such as firms' propensity to downsize or relocate in response to climate change policy. In all six countries and in most industries we studied, firms report an average downsizing risk well below a 10% cut in production or employment. In none of the industries did we find that the average firm will close down entirely and relocate to a non-European country. There is, however, substantial variation in the reported vulnerability between sectors as well as individual firms. This indicates that the EU's approach of exempting entire industries from permit auctions may not be efficient.

We explore this idea by developing a normative framework for industry compensation under the threat of relocation. Since free permits are revoked and cancelled when a firm exits, we assume that the propensity to relocate is declining in the amount of free permits a firm receives. The government allocates a fixed amount of permits so as to minimize the sum of relocation propensities across firms, weighted by the damage caused by relocation. This amounts to minimizing the aggregate expected damage of relocation. When damage is expressed in terms of CO_2 emissions, this objective function formalizes the EC's notion of 'carbon leakage risk'. An alternative specification we consider minimizes 'job risk', i.e. the expected amount of jobs lost due to relocation.[4]

[4]A key insight of the recent literature on the employment effects of environmental regulation is that the number of jobs lost is necessary but not sufficient for calculating the social costs of regulation. This is because laid-off workers may eventually find new jobs – though they suffer earnings losses and transitional unemployment while the economy adjusts to the new regulations

The upshot of the model is that free permits should be given to those firms where they have the highest *marginal* impact on total relocation risk (i.e. carbon leakage or job risk). Using the interview data, we show that this marginal impact varies substantially across firms and sectors, and that it is not necessarily correlated with the impact *level*. Counterfactual simulations reveal that optimal allocation dramatically reduces relocation risk, even compared to the situation where all permits are handed out for free. We also consider the dual problem of minimizing the number of permits handed out for free while constraining relocation risk. We find that the amount of relocation risk induced by the allocation rules for phase III of the EU ETS could be achieved with just a fraction of the amount of permits that will be handed out for free. The mismatch between optimal and actual allocations is particularly severe when it comes to minimizing job risk. Thus, although the exemption criteria were designed to protect the competitiveness of the most vulnerable industries, they do too little to mitigate the expected employment impact of carbon pricing.

A practical difficulty with implementing this optimal firm-level compensation scheme is that firms' vulnerability to carbon pricing is not publicly observable. We therefore derive optimal permit allocations under the 'feasibility constraint' that the allocation rule is a function of easily observable firm characteristics. We find that even simple rules, based on firm-level employment and carbon emissions alone, substantially reduce both carbon leakage risk and job risk.

Our analysis of the efficiency of free permit allocation in the EU ETS contributes important evidence pertaining to a difficult and contentious policy issue. Overcompensating carbon-intensive industries in times of broad public spending cuts might nourish a political backlash against emissions trading. The evidence presented in this paper will inform the EC's revision of the exemption criteria, envisioned for 2014, but its relevance transcends the European policy context. The EU ETS — and in particular its approach to preventing industrial relocation and carbon leakage— serves as a prototype for new and emerging regional trading schemes

(Walker, 2013). In his review of this literature, Bartik (2013) concludes that the social cost of such employment impacts are very uncertain because they should also account for possible multiplier effects, the price of leisure, and firm profits, among other things. He estimates the social costs of jobs lost due to various environmental regulations in the U.S. at between 8 and 32 percent of the associated earnings.

worldwide. Specifically, Australia, California, Korea, New Zealand, and Switzerland have already adopted the EU's exemption criteria with minimal changes. Therefore, it is important to analyze how accurately these criteria identify the firms and sectors most vulnerable to carbon leakage.

Our model captures the basic trade-off between the costs of compensation and the expected damage of relocation, while allowing great flexibility in the way these objects are specified. Therefore, our main result that compensation should be tied to marginal rather than total relocation propensities applies to a broad array of settings where the regulator faces a credible threat of relocation on the part of the regulated firms. In devising efficient compensation schemes, our approach enhances political legitimacy of industry compensation, which is much needed when such compensation clashes with general norms of policy-making such as the polluter-pays principle.

The next section describes the process of free permit allocation in the EU ETS and summarizes the related literature. Section 3 describes the data set, particularly how we measure firm-level vulnerability to carbon pricing. Section 4 presents a normative framework for optimal permit allocation under relocation risk and conducts several counterfactual experiments under alternative constraints. Section 5 concludes.

2 Permit allocation in the EU ETS

Designing a cap-and-trade scheme inevitably requires a choice to be made about the initial allocation of permits. Unless all permits are auctioned off, the regulator has to determine the micro-allocation of permits across firms, across sectors, and – in an international emissions trading scheme such as the EU ETS – across countries. Initial permit allocation in phases I and II of the EU ETS followed a decentralized process. Countries were called upon to draw up National Allocation Plans that both fixed the national cap and determined the sectoral allocation. The majority of countries chose to "grandfather" existing business sites, i.e. they allocated emission permits for free based on historical emissions and adjusted for growth projections and the national contribution towards the EU's joint emission target under the Kyoto

Protocol.[5] Free allowances were granted to new entrants whereas the allowances of exiting facilities were revoked and cancelled.

For trading phase III, beginning in 2013, the EC envisioned a transition towards auctioning as the basic principle of allocation, which would transfer the ownership of emissions from incumbent polluters back to governments and, ultimately, taxpayers. Directive 2009/29/EC relegates the allocation of free emission allowances from national governments to Brussels and stipulates a harmonized allocation scheme to reduce competitive distortions among producers of similar products across member states. In what follows, we explain the two main features of this scheme, namely (i) the use of benchmarks which rewards operators who have taken early action to reduce the emission intensity of production and (ii) the continued free allocation to sectors considered at risk of carbon leakage.

2.1 Benchmarking

The Benchmarking Decision[6] stipulates that free allocation be based on product benchmarks to the extent possible. A product benchmark is defined as the average greenhouse gas emission performance of the 10% best performing installations in the EU producing that product, measured in tons of CO_2 equivalent per unit of output. An installation i producing an eligible benchmarked product j in year t receives an allocation of free permits given by

$$q^b_{ijt} = \text{benchmark}_j \cdot \text{historical activity level}_{i,j} \cdot \text{reduction}_{j,t} \cdot \text{correction}_t. \quad (1)$$

The benchmark of product j is based on the average emissions intensity in 2007-2008. The historical reference activity level is the median activity level over the years from 2005 until 2008 (or from 2009 until 2010, if larger). The number of free

[5] Ellerman et al. (2007) document that the principles guiding the development of National Allocation Plans in phase I were rather consistent across countries, as most opted for free permit allocations based on existing emissions. In phase II, governments imposed more stringent caps while retaining the allocation scheme. Auctioning fell far short of what was allowed and benchmarking remained an exception (Ellerman and Joskow, 2008).

[6] Commission Decision 2011/87/EU determining transitional Union-wide rules for harmonized free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (2011) OJ L 130/1 (Benchmarking Decision).

permits resulting from the first two terms in eq. (1) is scaled by two factors. First, the reduction factor takes a value of 0.8 in 2013 and declines linearly to a factor of 0.3 in 2020. No reduction occurs in sectors considered at risk of carbon leakage, for which the factor takes a value of 1 in all years. Second, a uniform correction factor is applied if necessary to align the total free allocation to benchmarked installations with the overall cap on emissions.

Where deriving a product benchmark is not feasible, allowances are allocated according to a hierarchy of fallback approaches. If a measurable heat carrier is used, benchmarks apply to heat consumption, otherwise they are tied to fuel consumption. If none of these approaches is feasible, the relevant benchmark is given by 0.97 times historical process emissions. Complex installations requiring various benchmarking techniques are first divided into sub-installations for which a single relevant benchmark can be used to determine allowance allocations.

A distinctive feature of the EU ETS is that free permit allocation is not tied to current production levels.[7] Rather, allowance allocation is based on production *capacity* prior to the trading phase and annual updates occur automatically via the linearly decreasing reduction factor. Only under exceptional circumstances do production choices entail an adjustment to the allowance allocation. On the one hand, if production drops by at least 50% relative to the historical activity level, a 50% reduction is applied to the free allowance allocation. If activity falls below 90%, free allocation will be ceased. On the other hand, in order to increase its permit allocation, an installation must undergo a net capacity increase of 15% or more, accompanied by a "significant increase in activity". New entrants receive free permit allocations according to the relevant benchmark, and activity levels are proxied for by multiplying the initial installed capacity by a standard capacity utilization factor. Compared to output-based updating, the capacity-based allocation rules in the EU ETS substantially limit an operator's ability to influence permit allocations by changing output and hence the impact of permit allocation on short-run production

[7] In contrast, carbon trading schemes in Australia, California or New Zealand establish "output based updating" where the benchmark is scaled by current output (Hood, 2010). The US case is analyzed by Burtraw et al. (2001); Bushnell and Chen (2012); Fischer and Fox (2007); Fowlie (2011). Monjon and Quirion (2011) analyze a hypothetical output based updating rule for the EU ETS.

decisions (Ellerman, 2008; Meunier et al., 2012).

2.2 Free allocation to sectors deemed at risk of carbon leakage

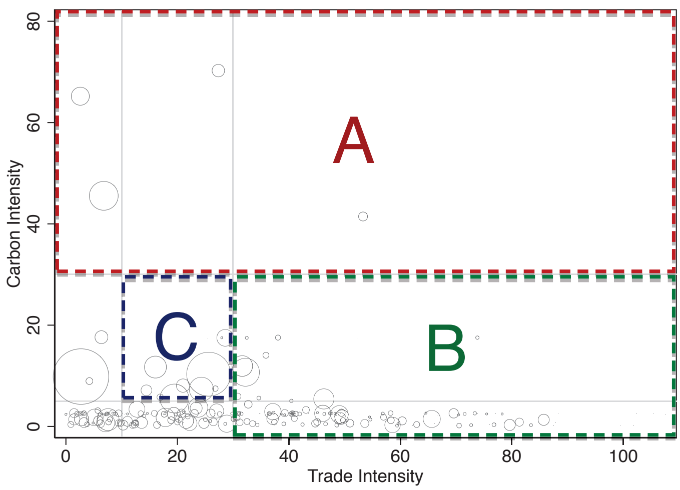
The gradual reduction in free allowances from 80% to 30% was met with strong opposition from carbon intensive industries, who convinced EU law makers that full auctioning of permits would exacerbate the detrimental impact of the EU ETS on their competitiveness. In order to mitigate such impacts, the EC will grant 100% of benchmark allocations for free to firms in sectors that are considered at risk of carbon leakage. The Carbon Leakage Decision[8] establishes leakage risk of a sector or subsector based on its carbon intensity (CI) and/or trade intensity (TI). CI proxies for the cost burden imposed by full auctioning, and is measured as the sum of the direct and indirect costs of permit auctioning, divided by the gross value added of a sector. The direct costs are calculated as the value of direct CO_2 emissions (using a proxy price of 30€/tCO_2). The indirect costs capture the exposure to electricity price rises that are inevitable on account of full permit auctioning in the power sector.[9] The TI metric is calculated as "the ratio between the total value of exports to third countries plus the value of imports from third countries and the total market size for the Community (annual turnover plus total imports from third countries)" (EU Commission, 2009, p. 24).

Directive 2009/29/EC stipulates a combination of thresholds for CI and TI to determine if a sector is at risk of carbon leakage. Sectors are considered at significant risk of carbon leakage if their CI is greater than 5% and their TI is greater than 10%, or either CI or TI is greater than 30%. We subdivide eligible sectors accordingly into three mutually exclusive categories: A – high carbon intensity (CI>30%), B – high trade intensity and low to moderate carbon intensity ($CI \leq 30\% \cap TI > 30\%$), and C – moderate carbon and trade intensities ($5\% < CI \leq 30\% \cap 10\% < TI \leq 30\%$). Figure 1 plots the location of 3-digit sectors in a diagram with CI on the vertical

[8]Commission Decision 2010/2/EU determining, pursuant to Directive 2003/87/EC of the European Parliament and of the Council, a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage (2010) OJ L 1/10 (Carbon Leakage Decision).

[9]They are calculated as electricity consumption (in MWh) multiplied by the average emission intensity of electricity generation in the EU27 countries (0.465 tCO_2/MWh), and applying the same proxy price for an European Union Allowance of 30€/tCO_2.

Figure 1: Sectors exempt from permit auctions



Notes: The figure shows a scatter plot of the carbon and trade intensities of 4-digit (NACE 1.1) manufacturing industries, based on 9,061 EU ETS installations. The size of the circles is proportional to the number of firms in a given industry. Sectors in areas A, B, and C will continue to be exempt from permit auctions in EU ETS phase III.

and TI on the horizontal axis.[10] It is evident that category B contains most of the sectors the EC considers at risk of carbon leakage, and that most of these sectors are not carbon intensive at all (i.e. CI<5%). We thus split category B according to its carbon intensity and plot in Figure 2 the relative size of the resulting five categories in terms of the shares in the number of firms, in employment and in CO_2 emissions.[11] By all these measures, category B turns out to be the largest group of exempted firms. The share of CO_2 emissions that is not exempt from auctioning is as small as 15%.[12]. This means that the Carbon Leakage Decision leaves most pollution rights with European industry and hence strongly undermines the principle of full auctioning established in the amended ETS directive.[13]

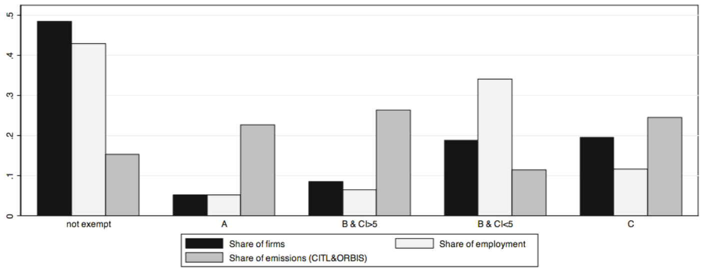
[10]In a critical appraisal of the Carbon Leakage Decision, Clò (2010) presents a similar visualization but does not show the size of sectors for lack of a match to firm-level data.

[11]Figure E.2 in the Appendix compares the size of these groups across different samples, namely (a) all EU ETS firms in the CITL/ORBIS matched sample, (b) all such firms in the six countries where we interviewed firms, and (c) all EU ETS firms we interviewed. This confirms that our interview sample is representative of the underlying population.

[12]There are a number of competing ways to compute this figure; e.g. a study by Juergens et al. (2013) finds a share of 23%

[13]In a companion paper, we analyze the empirical content of the carbon leakage criteria in more detail (Martin, Muûls, de Preux, and Wagner, 2013a)

Figure 2: Relative size of the exemption groups



Notes: The chart displays the relative size of each group of NACE industries which are defined by the exemption criteria. Category B (very trade intensive sectors) is subdivided into low and moderate carbon intensity. The sample includes the 4,254 manufacturing firms participating in the EU ETS and matched to ORBIS. The first bar indicates a group's share in the total number of firms, the second bar its share in employment, and the third bar its share in CO_2 emissions, based on the number of surrendered permits recorded in the CITL. To compute CI and TI figures at the NACE 4-digit level, we follow the methodology and databases used by the EU Commission (2009).

2.3 Related literature

How do these metrics relate to the profit impact of the EU ETS? On the one hand, previously grandfathered firms will be forced to pay the market price for the right to pollute. The CI measure is based on the assumption that the cost burden is proportional to the ratio of direct and indirect emissions to gross value added.

On the other hand, the demand response conditions a firm's ability to pass on this cost burden to its consumers in the form of higher prices. Doing so will be more difficult for a firm whose customers can easily substitute to relatively cheaper products from competitors located outside the EU. Import penetration is a widely used proxy for cost pass-through. However, the TI metric also contains the export ratio whose relation to the demand response is ambiguous. While the firm might be competing with non-EU firms for customers in its exports destinations, a higher export intensity also reflects the factor specificity of production which tends to mitigate the profit impact of permit auctioning.[14] In sum, there may be sectors that look vulnerable according to EU criteria although they can easily replace carbon intensive inputs by less carbon intensive ones, or pass-through the cost of permit

[14]For instance, a firm that benefits a lot from country specific factors – e.g. a skilled labor force, natural resource deposits, or externalities from industrial agglomeration – is less likely to relocate in response to full auctioning than a firm that can easily set up shop elsewhere. If factor specificity creates an absolute advantage (think of Swiss watches), TI will be high because of strong exports, not imports.

auctioning in international product markets.

There is little empirical evidence linking the EU criteria to a sector's vulnerability to carbon leakage.[15] In fact, the existing ex-post evaluation studies provide no evidence of strong adverse impacts of the EU ETS on competitiveness indicators when permits were allocated for free Anger and Oberndorfer (2008); Abrell et al. (2011); Bushnell et al. (2013); Chan et al. (2013); Commins et al. (2011); Wagner et al. (2013a,b). These studies use a broad set of indicators to analyze intensive-margin adjustments to production, employment and productivity (see Martin et al., 2013b, for a survey).

This paper extends previous research on the EU ETS by focusing on the extensive-margin impact. The compensation scheme we propose aims at preventing carbon leakage, following the EC's official justification for those transfers. This differs from the scheme used in a related literature concerned with the welfare costs of industry compensation in general equilibrium (Bovenberg and Goulder, 2002; Bovenberg et al., 2005, 2008). Not least, our paper adds to a rapidly growing literature linking firm-level data on management practices obtained in large-scale, cross-country surveys to official performance data in order to better explain firm-level productivity, energy efficiency and organizational structure (Bloom and van Reenen, 2007; Bloom, Genakos, Martin, and Sadun, 2010; Martin, Muûls, de Preux, and Wagner, 2012).

3 Data

This paper combines three principal sources of data into a unique firm-level data set suitable for analyzing the link between permit allocation and carbon leakage. First, we collect data on vulnerability to carbon pricing – as well as on management

[15] While theoretical and simulation based studies find a negative impact of the EU ETS on production in most manufacturing industries (e.g. Demailly and Quirion, 2006, 2008; Reinaud, 2005; McKinsey and Ecofys, 2006), they also show that free permit allocation offsets negative profit impacts in most industries and can even lead to overcompensation (Smale et al., 2006). These studies do, however, highlight adverse effects of rising electricity prices on the profitability of highly exposed industries such as primary aluminum production. Sato et al. (2007) review this literature and propose to use trade intensity, carbon intensity and electricity intensity as proxies for the competitiveness impact of the EU ETS.

practices relating to climate policy more generally – by interviewing managers of manufacturing firms in six European countries: Belgium, France, Germany, Hungary, Poland and the UK.[16] Second, we augment this information with "hard" data on economic performance from the ORBIS database maintained by Bureau Van Dijk. Third, we obtain data on CO_2 emissions from the official EU ETS registry, known as the Community Independent Transactions Log (CITL). Additional EU data sources are used to calculate carbon emissions, CI and TI at the sector level. This section describes the data collection and matching processes and summarizes our core data set.

3.1 Interview based measure of vulnerability to carbon leakage

To obtain a measure of the expected impact of future climate policies on outsourcing and relocation decisions, we asked managers:[17]

> "Do you expect that government efforts to put a price on carbon emissions will force you to outsource part of the production of this business site in the foreseeable future, or to close down completely?"

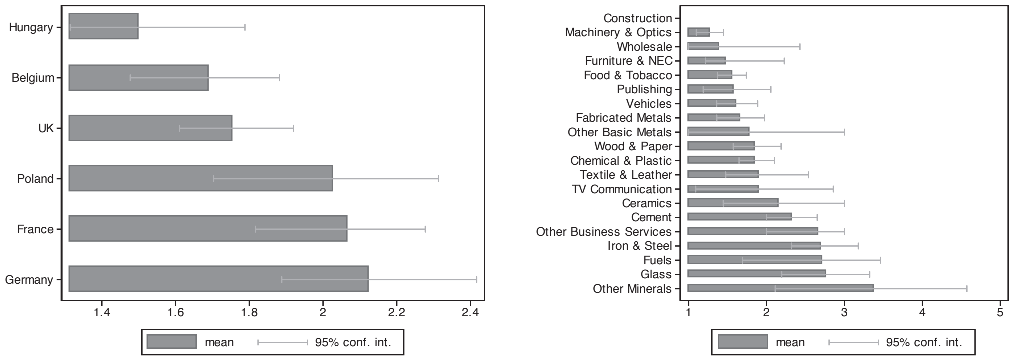
The answers to this question were translated into an ordinal 'vulnerability score' (VS) on a scale from 1 to 5. Analysts were instructed to assign a score of 5 if the manager expected the plant to be closed completely, and a score of 1 if the manager expected no detrimental impacts at all. A score of 3 was given if the manager expected that at least 10% of production and/or employment would be outsourced in response to future policies. Scores of 2 or 4 were given to account for intermediate responses.

VS across all firms in the sample has a mean of 1.87 and a standard deviation of 1.29. ETS firms expect a significantly higher impact of 2.14 than non-ETS firms (1.49). Inspection of the raw data suggests that carbon pricing will affect German and French and Polish firms more strongly than British, Belgian and Hungarian

[16] Scheduling of interviews began in late August 2009 and the last interview was given in early November 2009.

[17] See Appendix G for the exact wording and sequencing of the relocation questions.

Figure 3: Average vulnerability score by country and industry



(a) by country (b) by sector

Notes: The bars show the average score in a given country (a) or 3-digit sector (b). Bootstrapped confidence bands are calculated at the 95% level. NEC: Not elsewhere classified.

firms (cf. Figure 3a). However, in no country does the 95%-confidence band include outsourcing of more than 10% of production in response to regulation. Looking across different industries, fuels and other minerals, glass, iron & steel are the most vulnerable (cf. Figure 3b). In all other industries, the average VS is rather low. In no industry do we find that plant closure and complete relocation are in the 95% confidence interval.[18]

Further results (reported in Appendix Table A.5) show that only French firms expect significantly stronger-than-average impacts after controlling for industrial composition and interview noise.[19] Hence the heterogeneity in the responses is driven mainly by sectoral differences. Again controlling for interview noise, we find that other minerals, glass, iron & steel, and cement are the most vulnerable industries, irrespective of employment size. Other energy intensive industries such as food & tobacco, fabricated metals, and vehicles are significantly less vulnerable than the average.

[18]Figure A.1 in the Appendix shows the full distribution of the vulnerability score, by country and industry. Summary statistics are reported in Table A.4.

[19]The regressions underlying Table A.5 include interviewer fixed effects to control for possible bias on the part of the interviewers. They also control for interview noise due to the manager's characteristics – by including the tenure in the company, dummies for gender and professional background (technical or law) – and due to the time of the interview – by including dummies for month, day of week and time of day (am/pm).

3.2 Validity of the vulnerability score

Given the importance of the VS measure for the analysis to follow, we now describe key aspects of the interview design and the sampling procedure which help to minimize potential sources of bias. Additionally, we present evidence that our measure is *internally* consistent with other interview results, and that it is *externally* consistent, based on energy price elasticities of employment in a large sample of firms in Europe and other OECD countries.

Interview design We adopt a survey tool based on structured telephone interviews pioneered by Bloom and van Reenen (2007) and designed to avoid several sources of bias common in conventional surveys (Bertrand and Mullainathan, 2001). Unlike other survey formats, the interviewer engaged the interviewee in a dialog with specific questions for discussion. On the basis of this dialog, the interviewer then assessed the company along various aspects of management relevant for climate policy, including VS. We provided exemplary responses that interviewers could consult when in doubt about giving a high versus a medium or low score for the relevant dimension. The goal was to benchmark the practices of firms according to common criteria. For instance, rather than asking the manager for a subjective assessment of the management's awareness of climate change issues we gauged this by how formal and far-reaching the discussion of climate change topics was in current management.

As in Bloom and van Reenen (2007), the interview process was "double blind". Interviewees were not told that their answers would be scored, so as to avoid giving them an incentive to provide biased information. Conversely, interviewers were given no information about the firm except the contact details, so as to minimize the chance that their preconceptions about the firm could influence the scoring process.[20] For consistency checks of interviewer scoring, a subset of randomly selected interviews were double-scored by a second team member who listened in.

[20]Given our focus on medium-sized firms, the graduate students conducting the interviews were unlikely to have prior knowledge about the firm they were interviewing (Bloom and van Reenen, 2010).

Random sampling Our sampling frame comprised all manufacturing firms with more than 50 but less than 5,000 employees contained in ORBIS for the countries under study. Out of a total of 44,605 such firms, possible interview partners were drawn at random and contacted via phone until an interview was given or explicitly denied. We oversampled EU ETS firms by drawing firms at random from the EU ETS registry so that between 50% and 70% of managers contacted in each country worked at an EU ETS firm. In total, we contacted 1,451 firms in the six countries and interviewed 761 of them (131 firms in Belgium, 140 in France, 138 in Germany, 69 in Hungary, 78 in Poland, and 209 in the UK). Of all firms we interviewed, 446 (57%) were in the EU ETS. In spite of a relatively high response rate of 53% (68% among EU ETS firms and 39% among the rest), sample selection bias might arise if interviewed firms differ in systematic ways from firms that declined to be interviewed. We compare the principal firm characteristics available in the ORBIS database – turnover, employment and capital – between firms interviewed and not interviewed, conditional on a firm's participation in the EU ETS. These comparisons are reported in Section A.2 of the Appendix and show no statistically significant evidence of sample selection on observable characteristics.

Internal consistency Table 1 shows that VS correlates in expected ways with other interview responses that also capture vulnerability to carbon pricing in some way but may be deemed less subjective. A low VS is strongly associated with a high cost pass-through as well as with a low share of non-EU competitors. Both circumstances enable firms to pass the cost of carbon pricing on to their customers and thus help to protect them against the detrimental effects of carbon pricing. Moreover, we find a strong positive association between VS and a number of management practices relevant for climate change, such as the setting, monitoring and enforcement of targets for energy consumption or GHG emissions, as well as process innovation in areas related to climate change. This is plausible as the firms most adversely affected by carbon pricing have stronger incentives to monitor and reduce their carbon intensity and permit liability. When the sample is restricted to include only EU ETS firms, similar qualitative findings emerge although the statistical significance on some of the management variables is lower. In sum, these results support

Table 1: Correlations between vulnerability score and other interview variables

	(1) All firms	(2) EU ETS firms
Cost pass-through (%)	-0.107***	-0.109*
Share of non-EU competitors (%)	0.141***	0.135**
Non-EU competitors	0.02	-0.06
Total competitors	0.02	-0.14
Share of sales exported to non EU (%)	-0.08	-0.03
Customers are other businesses (D)	0.105***	0.166***
Multinational firm (D)	0.01	-0.06
CC related products (S)	0.01	0.01
CC related product innovation (S)	-0.02	-0.04
CC related process innovation (S)	0.132***	0.108*
Energy monitoring (S)	0.169***	0.179***
Greenhouse gas monitoring (S)	0.168***	0.1
Energy consumption targets (S)	0.074*	0
Greenhouse gas targets (S)	0.207***	0.160***
Enforcement of targets (S)	0.120***	0.1
Employment	0.02	-0.06
EU ETS firm (D)	0.623***	

Notes: Coefficients of correlation between the vulnerability score and other interview variables. Variables refer to numbers unless indicated otherwise; D denotes a dummy variable and S another interview score constructed in a way similar to the vulnerability score. CC stands for "climate change". Results in column 1 are based on the full sample wheras those in column 2 are calculated using only firms in the EU ETS. Asterisks indicate statistical significance at the 10% (*), 5%(**) and 1%(***) level.

the internal consistency of VS as a measure of the firm's vulnerability to carbon pricing.

External consistency If VS is a valid measure of a firm's propensity to outsource jobs in response to higher carbon prices, one would expect that high VS firms respond to higher energy prices in a similar fashion, especially if energy prices in alternative locations abroad remain low.[21] To test this hypothesis, we examine whether energy price elasticities of employment are negatively correlated with our VS measure across sectors. To this end, we regress manufacturing employment on the difference between energy prices at home and abroad, using more than 460,000

[21] Following common practice in empirical economics, we use the energy price as a proxy where carbon price data are not available for lack of relevant policies (e.g. Popp, 2002).

firm-year observations from ORBIS.[22] The energy price differential is calculated at the sector level by subtracting the inverse-distance weighted mean of energy prices abroad from the domestic energy price. To control for differences in labor costs we also include the wage differential, calculated in the same fashion. Factor price differentials vary at the industry, country and year levels. We interact these price variables with different transformations of the VS variable to test for heterogeneous employment responses to changing energy prices. Our regression model allows for firm fixed effects, a full set of country-year effects, and sectoral trends. This controls for unobserved heterogeneity across firms, for transitory shocks at the macro level, and for differences in employment trends across sectors, respectively. We implement this regression using the dynamic panel estimator by Blundell and Bond (1998), which controls for endogenous prices and serially correlated error terms. Section B.1 in the Appendix describes the data and methods used in detail.

Table 2 reports the elasticity estimates based on data for the years 2001 through 2007, separately for a sample of 20 OECD countries and a sample of 16 European countries. We interact the price variables (i) with a dummy indicating whether a firm belongs to a sector with above-median VS (High VS), or (ii) with the deviation of the sector VS from the overall VS mean. In each case, we find strong evidence that the employment response to an increase in the energy price differential decreases with the sector's VS. For instance, column 1 reports a small positive energy price elasticity of 0.046 for sectors with below-median VS values.[23] For "High VS" sectors this elasticity is 0.019 lower. This effect is economically significant as it accounts for 41% of the total effect for the reference group. Similarly, column 2 reports that firms in sectors whose VS is 1 score point above the overall mean exhibit an energy price elasticity that is 0.007 lower than the average, which is economically significant as well.[24] The results in columns 3 and 4 are very similar.

[22]Estimating the elasticity in this way abstracts from substitution effects that occur when both home and foreign energy prices change by the same amount. In fact, the domestic energy price should matter for relocation only if energy prices in alternative locations are lower.

[23]That is, a doubling of the energy price differential leads to a 4.6 percent increase in employment. Note that we have no priors about the absolute sign of the elasticity. The net impact on employment depends on the relative size of a substitution effect (positive) and an output effect (negative).

[24]Increasing a sector's mean VS by two standard deviations (+1.76) reduces the employment elasticity w.r.t. to the energy price differential by 0.012. This reduction amounts to one third of the

Table 2: Estimates of the energy-price elasticity of employment in vulnerable sectors

	(1)	(2)	(3)	(4)
	Employment			
	OECD		European Union	
Employment$_{t-1}$	0.966***	0.966***	0.950***	0.949***
	(0.006)	(0.006)	(0.007)	(0.007)
Relative Energy Price [EP^D-EP^F]	0.046***	0.038**	0.089***	0.072***
	(0.018)	(0.018)	(0.016)	(0.016)
× High VS	-0.019***		-0.026***	
	(0.004)		(0.004)	
× VS-mean(VS)		-0.007***		-0.009***
		(0.002)		(0.002)
Country-by-year effects	yes	yes	yes	yes
Sector trends	yes	yes	yes	yes
Firms	113,680	113,680	94,398	94,398
Observations	464,272	464,272	396,182	396,182

Notes: The dependent variable is firm-level employment measured on a logarithmic scale. The domestic EP index is calculated as the average price across different fuel types (in logs), with constant expenditure weights. The foreign EP is the average EP in all foreign countries, inversely weighted by the geographical distance to that country. The vulnerability score (VS) is the sectoral employment-weighted average of the firm-level VS. High VS indicates a VS above the median. The regressions also include a full set of country-year effects and sectoral trends. The sample comprises all ORBIS firms that reported 10 or more employees at least once between 1999 and 2007. The OECD sample comprises 20 OECD countries (listed in Appendix B.1). In columns 3 and 4, non-EU countries are excluded from the sample and Romania is included. All regressions are implemented with the System GMM by Blundell and Bond (1998). Robust standard errors, clustered at the firm level, are in parentheses. Asterisks indicate statistical significance at the 10%(*), 5%(**) and 1%(***) levels.

In sum, these regressions show that the VS – which indicates a higher chance of downsizing domestic operations in response to higher carbon prices – is consistent with how manufacturing firms in Europe and in the OECD adjust their labor input in response to the energy price differential between domestic and foreign locations.

Expectations about free allocation The question underlying VS was asked within the hypothetical policy context of firms not receiving *any* free permits. This is a counterfactual scenario, not just because manufacturing firms had been receiving free permits throughout the first two phases of the EU ETS, but also because many of them could expect to receive free permits to cover a non-negligible share of their emissions even in Phase III.

Respondents were not explicitly instructed to consider the no free allocation

main effect (0.038) of the energy price differential, and to more than half of the main effect of the wage differential on log employment (-0.022, cf. Appendix Table B.2).

scenario when the initial relocation question was posed. If respondents anchored their answers to the expected allocation of free permits, rather than to the hypothetical scenario we described to them, this would likely induce downward bias in the VS.

Directive 2009/29/EC specifying the criteria and thresholds for free allocation to sectors at risk of carbon leakage was published four months before we started the interviews. Therefore, we cannot rule out the possibility that some respondents correctly anticipated that they would receive free permits. If this expectation had a systematic effect on responses, then we should observe a discrete jump in VS around the thresholds. We examine this using a regression discontinuity design that accommodates multiple assignment variables. For a variety of specifications and functional forms, the effect of thresholds on VS is not significant. We thus cannot reject the hypothesis that the available information on free permit allocation did not influence the responses to the hypothetical question underlying VS.[25] A detailed description of this analysis is relegated to Appendix B.2.

3.3 Data on economic performance and carbon emissions

Balance-sheet data on firm performance and other characteristics are obtained from ORBIS. Table 3 summarizes selected variables for the sample of 761 firms we interviewed. The sample is well stratified with respect to age, size, profitability, and ownership. Table A.3 in the Appendix compares the sample means of each characteristic between firms in the EU ETS with those that are not and reports the results from a test of equality group means. This reveals that EU ETS firms are older, larger and more profitable than their counterparts outside the EU ETS, and that these differences are statistically significant.

Data on carbon emissions and permit allocations for all EU ETS firms in the sample are calculated as the average, respectively, of verified emissions and allo-

[25]Given this result, it seems unlikely that firms not at risk of carbon leakage would underreport their vulnerability due to the prospect of free allowances under the benchmarking rules. Free allocations to those firms will be as small as 30% of benchmark emissions in 2020. Moreover, the Benchmark Decision was published in May 2011, i.e. 18 months after the completion of the interviews. This means that the political uncertainty these firms faced about how many free allowances they would get was much larger than for the sectors covered by the Carbon Leakage Decision.

Table 3: Firm characteristics

	Mean	Standard deviation	Percentiles 10th	50th	90th	Obs.
Firm						
Age (years)	37	37	7	22	87	736
Turnover (EUR million)	477.69	2,790.11	9.79	77.20	728.37	696
Number of employees	1,004	3,891	84	298	1,890	699
EBIT (EUR million)	17.18	78.25	-1.85	2.31	41.65	683
Number of shareholders	2	5	1	1	3	761
Number of subsidiaries	4	24	0	1	8	761
Firm's Global Ultimate Owner						
Turnover (USD million)	23,800	54,100	176	5,948	57,500	241
Number of employees	46,804	72,634	492	15,211	107,299	226

Notes: EBIT: Earnings Before Interests and Taxes. Interview data sample of 761 firms. Figures correspond to the year 2007. Source: ORBIS (Bureau Van Dijk).

cated permits between 2005 and 2008 obtained from CITL. Benchmark allocations for phase III are taken from the National Implementation Measures (NIMs). We aggregate these installation-level variables up to the firm level before matching them to ORBIS.

EU ETS firms interviewed by us are sampled either from ORBIS or from the CITL. They are subsequently matched to the CITL or ORBIS, by hand (in the case of Germany, Hungary and the UK) or using lookup tables available in the public domain (in the case of France, Belgium and Poland). This also allows us to assign firms in the CITL to 4-digit NACE industrial sectors.[26] To match firms and countries that are not included in our interviews or in official lookup tables, we draw on a mapping from CITL to ORBIS by Calel and Dechezleprêtre (2012).[27] This allows us to match 75% of CITL installations and emissions to ORBIS firms. NACE rev 1.1 classification and employment data is available for 4,254 firms, 71% of which are manufacturing firms. Table E.1 of the Appendix summarizes the correspondence between sectoral classifications.

[26]NACE stands for "Nomenclature statistique des activités économiques dans la Communauté européene" (Statistical Classification of Economic Activities in the European Community).

[27]We thank Rafael Calel and Antoine Dechezleprêtre for graciously providing us with NACE code identifiers and employment data based on their mapping. The match comprises 5,037 firms (9,061 installations) with a total of 1,743 million tons of CO_2.

4 Optimal permit allocation

In a cap-and-trade scheme, the permit price is determined by the total cap and the marginal cost schedules of all regulated firms. Therefore, the way in which the total cap is allocated across firms should have no bearing on marginal production decisions. However, permit allocation directly affects firm behavior at the extensive margin through its impact on firm profits, because a firm that exits or relocates loses its permit endowment.[28] This section develops a simple normative model of permit allocation where the government's principal concern is to prevent the relocation of production to places where carbon regulation is less stringent.

4.1 Model setup

We consider a firm i that is located in a regulated country and earns a profit of $\pi_i(p,q_i)$ which depends on the number of free permits q_i allocated to the firm and on the prevailing permit price p. Since free permits can be regarded as a lump-sum subsidy to the firm we assume that $\frac{\partial \pi_i(p,q_i)}{\partial q_i} > 0 \; \forall \; p > 0$. By relocating to an unregulated country f, firm i would obtain profit π_{if} and incur relocation cost κ_i. The firm relocates if $\pi_i(p,q_i) < \pi_{if} - \kappa_i$. We assume that the government has accurate information on the firm's profits at home but cannot observe the net cost of relocation $\varepsilon_i \equiv \kappa_i - \pi_{if}$. The government only knows that ε_i is an *iid* random variable with mean μ_ε and standard deviation σ_ε and that it follows a continuously differentiable distribution function $F_i(\cdot)$. Given the binary relocation variable

$$y_i \equiv \mathbf{1}\{\varepsilon_i < -\pi_i(p,q_i)\} \tag{2}$$

the government's assessment of the probability that firm i relocates is thus given by $\Pr(y_i = 1|p,q_i) = F_i[-\pi_i(p,q_i)]$.

The revised Emissions Trading Directive 2009/29/EC grants compensation to polluting industries both to protect their international competitiveness and to prevent carbon leakage. We formalize these policy objectives by assuming that the

[28] Since the capacity based updating in phase III does not affect short-run production choices (cf. Section 2.1 above), we choose to model free permit allocation to existing firms as a lump-sum transfer. We explore the implications of output-based updating in Appendix D.

government minimizes the total expected damage of relocation, expressed in terms of carbon leakage or jobs lost. For brevity, we refer to the objective as 'relocation risk', or use the terms 'carbon leakage risk' or 'job risk' whenever the damage is specified.

The contribution to aggregate relocation risk by individual firm i is given by

$$r_i(q_i) = F_i\left[-\pi_i(p,q_i)\right]\cdot\left[\alpha l_i(p) + (1-\alpha)e_i(p)\right] \tag{3}$$

where $l_i(p)$ and $e_i(p)$ denote the level of employment and emissions at firm i at permit price p, respectively, and α their relative weight in the government's damage assessment. Thus, it is assumed that, when firm i relocates to a non-EU country, all of its jobs are lost and all of its emissions "leak" to non-regulated countries. In what follows, we take the total cap $\bar{Q}$ to be exogenously fixed. Therefore, the carbon price is constant and will be omitted hereafter for ease of notation.[29]

The government chooses how many permits q_i to allocate to each firm i so as to minimize aggregate relocation risk $R = \sum_{i=1}^{n} r_i(q_i)$ subject to the sum of allocated permits not exceeding the overall cap $\bar{Q}$:

$$\min_{\{q_i \geq 0\}} \sum_{i=1}^{n} r_i(q_i) \text{ s.t. } \sum_i q_i \leq \bar{Q}. \tag{4}$$

Given the assumptions on F_i, an additional free permit always brings about a marginal reduction in the probability of relocation. Hence the shadow price λ of a permit is positive and the permit constraint holds with equality. The first-order condition for an interior solution is given by

$$F_i'\left[-\pi_i(q_i)\right]\frac{\partial \pi_i(q_i)}{\partial q_i}\left[\alpha l_i + (1-\alpha)e_i\right] = \lambda \qquad \forall i. \tag{5}$$

Equation (5) requires the regulator to equalize, for each firm, the reduction in expected job losses and carbon leakage brought about by the last free permit allocated to that firm.

[29]The carbon price could vary as the overall distribution of abatement costs changes when some facilities exit. Since our primary concern is with the elasticity of profits w.r.t. free permit allocation, we leave this as a topic for future research.

To appreciate the emphasis on the marginal relocation probability, consider two firms with identical levels of employment and abatement at price p^c but with different relocation probabilities. Optimality requires that the government allocate the bulk of free permits not to the firm with the highest relocation propensity but rather to the firm where these permits bring about the largest *reduction* in the relocation probability, weighted by a convex combination of jobs and emissions at the firm. Although this important insight follows immediately from straightforward economic reasoning, it has not been voiced in the public debate on free permit allocation so far.

Consider now the dual of program (4) which seeks to minimize the amount of free permits allocated to the firms subject to the constraint that relocation risk does not exceed the level $\bar{R}$:

$$\min_{q_i \geq 0} \sum_{i=1}^{n} q_i \text{ s.t. } \sum_{i=1}^{n} r_i(q_i) \leq \bar{R} \tag{6}$$

It is easily seen that the first-order condition for an interior solution to this program requires that the impact on relocation risk of the last free permit be equal across all firms receiving positive amounts of permits, as was shown above for the primal program.

4.2 Numerical solution

In solving for the optimal permit allocation we want to allow for firm-specific relocation probability functions $F_i(\cdot)$ and for corner solutions that can arise when the marginal impact of the first permit on relocation risk at a firm falls short of its shadow value. This suggests a numerical approach to solving programs (4) and (6) based on standard dynamic programming techniques.[30]

For an arbitrary ordering of firms, the recursive formulation of program (4) yields the Bellman equation

$$V_i(s_i) = \min_{0 \leq q_i \leq s_i} F_i[-\pi_i(q_i)]\,[\alpha l_i + (1-\alpha)e_i] + V_{i+1}(s_i - q_i) \tag{7}$$

where s_i is the amount of total permits left when reaching firm i and $V_{i+1}(s_i - q_i)$

[30] Appendix C provides further information on the computational details.

is the value of leaving $s_i - q_i$ permits to all remaining firms in the sequence. It is straightforward to solve eq. (7) numerically, starting with the last firm N in the sequence whose value function is given by $V_N(s_N) = F_i[-\pi_N(s_N)][\alpha l_N + (1-\alpha)e_N]$. For firms earlier in the sequence, we iterate on (7) to choose the optimal q_i for each possible s_i. The same approach allows us to solve the dual problem (6) after inverting eq. (3) to get $q_i = \pi_i^{-1}\left[-F_i^{-1}\left(\frac{r_i}{\alpha l_i + (1-\alpha)e_i}\right)\right]$. Rather than allocating the pieces of a fixed pie of free permits so as to reduce total risk, we now allocate the pieces of a fixed pie of relocation risk so as to minimize total permits. The analogue to Bellman equation (7) is given by

$$W_i(s_i) = \min_{0 \le r_i \le s_i} \pi_i^{-1}\left[-F_i^{-1}\left(\frac{r_i}{\alpha l_i + (1-\alpha)e_i}\right)\right] + W_{i+1}(s_i - r_i) \tag{8}$$

and can be solved recursively in the same fashion as described above.

Calculating the marginal propensity to relocate We assume that the unobserved net cost of relocation follows a logistic distribution and consider a linear approximation to the profit function $\pi_i(q_i) = \delta_{0i} + \delta_{1i}q_i$.[31] This yields the relocation probability

$$\Pr(y_i = 1|q_i) = F_i(-\pi_i(q_i)) = \frac{1}{1 + \exp(\beta_{0i} + \beta_{1i}q_i)} \tag{9}$$

with parameters $\beta_{0i} \equiv \frac{\delta_{i0} + \mu_\varepsilon}{\sigma_\varepsilon}$ and $\beta_{1i} \equiv \frac{\delta_{1i}}{\sigma_\varepsilon}$. We calibrate these parameters for each firm based on the interview responses. While the VS captures the managers' assessment of the future impact of carbon pricing on their businesses under the assumption of no free allocation, we obtain its gradient by asking how the VS would change if the company was granted permits for 80% of its emissions at no cost.[32] For a given mapping from the VS into relocation probabilities,[33] this allows us

[31] We allow the coefficient on free permits to vary across firms to account for the fact that the present value of free permits allocated during phase III varies across firms. This reflects differences in capital costs due to risk, taxation, and access to credit.

[32] This corresponds to questions 12a and 12c of the interview, cf. Appendix G. Figure E.1 in Appendix E shows the distribution of the change in vulnerability conditional on the initial VS.

[33] We follow the interview scoring grid in assigning probabilities of 0.01, 0.10 and 0.99 to scores 1, 3 and 5, respectively. We interpolate between these numbers and assign probabilities of 0.05 and

to evaluate the relocation probability with no free permits, $\Pr_i(y_i = 1|q_i = 0)$ as well as with 80% free permits $\Pr_i(y_i = 1|q_i = 0.8e_i)$ and use these to back out the parameters $\beta_{0i} = \ln\left[\frac{1-\Pr_i(y_i=1|q_i=0)}{\Pr_i(y_i=1|q_i=0)}\right]$ and $\beta_{1i} = \frac{1}{0.8e_i}\ln\left[\frac{1-\Pr_i(y_i=1|q_i=0.8e_i)}{\Pr_i(y_i=1|q_i=0.8e_i)} - \beta_{0i}\right]$ in equation (9).

4.3 Simulation of counterfactual allocations

We compute optimal allocations under different assumptions about the government's objective function (risk vs. cost minimization), about the damage weights (job loss vs. carbon leakage), and about the level at which free permits are allocated (firm or sector). Counterfactual permit allocations provide a benchmark against which to compare *de facto* permit allocations in phase II (grandfathering) and phase III (benchmarking), so as to quantify the efficiency costs of these allocations.

Minimizing relocation risk Table 4 compares the relocation risk associated with the free permits handed out under grandfathering or benchmarking (in column 1) with the minimal risk, subject to the constraint that the total number of free permits matches the amount handed out in the reference scenario (in column 2). The first row shows that job risk under grandfathering can be reduced from 4.2% to 2.9% of employment in EU ETS sectors when permits are allocated optimally across firms. With benchmarking, job risk increases by two thirds to 6.9% of ETS employment. Optimal redistribution of permits to firms brings the risk back down to 2.9%. To account for sampling error surrounding these point estimates, we report the bootstrapped 95th percentile of each statistic in brackets. This shows that the risk to jobs amounts to at most 4.7% of ETS employment in 95 out of 100 cases. Moreover, while the average reduction in job risk compared to the benchmarking scenario is almost 4 percentage points, a reduction by at least 1.9 percentage points can be achieved with 95% probability.

Panel B of Table 4 reports the risk of carbon leakage as a share of total emissions covered by the ETS for the same allocations. The baseline risk, which at 15.7% is

0.55 to scores 2 and 4, respectively.

Table 4: Risk of job loss and carbon leakage

	(1)	(2)	(3)	(4)	(5)
Reference scenario	Actual Risk	Minimized Risk		Change in Risk	
A. Percentage share of ETS employment at risk					
Grandfathering	4.16	2.93	3.23	-1.23	-0.93
		[4.66]	[5.03]	[-0.56]	[-0.37]
Benchmarking	6.92	2.94	4.51	-3.98	-2.41
		[4.66]	[6.54]	[-1.92]	[-0.46]
B. Percentage share of ETS emissions at risk					
Grandfathering	15.66	13.15	14.34	-2.51	-1.32
		[23.88]	[24.16]	[-0.36]	[-0.22]
Benchmarking	22.79	13.20	21.91	-9.59	-0.88
		[23.89]	[31.80]	[-4.45]	[3.18]
Optimized over	-	Firms	Sectors	Firms	Sectors

Notes: Shares of jobs (panel A) or CO_2 emissions (panel B) at risk of relocation are expressed relative to total employment or emissions at all ETS firms in the sample. Column 1 reports actual risk associated with a given reference scenario (grandfathering or benchmarking) whereas columns 2 and 3 report minimal risk subject to the constraint that the total number of free permits not exceed the amount allocated under the reference scenario. Permit allocation is optimized across firms (column 2) or across sectors (column 3). Columns 4 and 5 report the change in risk after optimization. In addition to the point estimates, columns 2 through 5 report the 95th percentiles in brackets, obtained from a non-parametric bootstrap with resampling.

higher than the job risk, increases by almost half to 22.8% under benchmarking. Efficient allocation reduces the leakage risk to just above 13% for either permit constraint. When benchmarking is taken as the reference scenario, optimal permit allocation reduces the average leakage risk by 9.6 percentage points. Accounting for sampling error, the risk reduction is at least 4.5 percentage points with 95% probability.

Furthermore, we calculate minimal relocation risk under the additional constraint that the government cannot assign free permits at the firm level but only at the sector level. This is meant to take into account political constraints that led the EC to establish exemption criteria at the 4-digit sector level. We assume that a firm receives permits according to its share in the sector's total emissions under grandfathering and aggregate the resulting relocation risk across firms within sectors. The results in columns 3 and 5 of Table 4 show that both job and leakage risks are higher than with firm-level allocations.[34] While sector-level allocation still re-

[34]The constraints on the number of free permits are binding now because grandfathering individ-

duces job risk compared to benchmarking – at least 0.5 percentage points with 95% probability, and 2.4 percentage points on average – this is not guaranteed anymore for CO_2 risk. In fact, the 95th percentile of the risk change reported in column 5 is positive. Unlike grandfathering, benchmarking sometimes leads to lower leakage risk than optimal sector-level allocations. These efficiency gains can be attributed to the within-sector allocation of permits and partly justify the considerable administrative effort that went into benchmarking.

Cost minimization Minimizing the amount of free permits subject to a given relocation risk can be regarded as the tax payer's cost minimization program because it minimizes the amount of foregone auction revenue for a given outcome. Table 5 displays the share of permits handed out for free under different allocation schemes. The first row shows that optimal allocation at the firm level gives rise to drastic efficiency gains. The relocation risk associated with grandfathering could be achieved by handing out only between 14.3% and 24.5% of permits for free, depending on whether job risk or carbon leakage risk is held fixed.[35]

Under benchmarking, a large number of sectors and particularly the carbon-intensive ones will continue to be exempt from permit auctioning. As a consequence, 52.3% of emissions will continue to be allocated for free. This propels the job risk to a very high level that could be achieved by optimally allocating free permits for a mere 1.6% of total emissions. Carbon leakage risk also increases substantially with benchmarking. Obtaining this level of leakage risk at minimal cost would require just under 13% of permits to be allocated for free. Given that sampling error may affect the point estimates, one can make the more cautious statement that, with 95% probability, the level of job risk induced by the benchmarking rules could be achieved by allocating at most 7.0% of the permits for free.

ual firms with a high marginal impact of free permits is more costly under sector-level allocation as all other firms in the sector must be given free permits as well. Clearly, those permits are then not available anymore to grandfather more vulnerable firms in other sectors.

[35]Two mechanisms drive this result. First, the majority of firms in our sample report that their propensity to relocate does not vary with the amount of free permits. It is optimal to assign zero free permits to those firms. Second, among the remaining firms, free permits are allocated in such a way as to equalize the marginal propensity to relocate, weighted by jobs or carbon emissions, as required by the first-order condition (5).

Table 5: Permits allocated for free (in % of total emissions)

Scenario	(1) Actual	(2) Minimized	(3) Allocation
Grandfathering	100.0	14.3	24.5
		[31.4]	[39.2]
Benchmarking	52.3	1.6	13.0
		[7.0]	[22.3]
Risk constraint	-	Jobs	CO_2

Notes: Column 1 reports the share of free permits in total emissions under different scenarios. Minimal permit allocations are calculated subject to the constraint that the total relocation risk not exceed the one under the scenario considered, where relocation risk is measured in terms of either job loss ($\alpha = 1$) or CO_2 emissions leakage ($\alpha = 0$). The 95th percentile of the permit share, obtained from a non-parametric bootstrap with resampling, is reported in brackets.

The corresponding figure for carbon leakage risk is 22.3%. This means that EU governments could raise additional revenue by auctioning a much larger amount of emissions permits instead of allocated them free, without increasing the expected cost of carbon leakage or job loss.[36]

4.4 Feasible optimal permit allocation

We have shown above that allocating permits optimally will significantly reduce relocation risk compared to the Benchmarking scheme currently in place. Since this approach relies on information that is not publicly observable and easy to manipulate, a possible future survey would need an appropriate mechanism to induce firms to report their vulnerability to carbon pricing truthfully. In this section we take an alternative approach and use the survey information to develop simple allocation rules which are based on easily observable characteristics of firms.

Given a total amount of free permits $\bar{Q}$, an allocation share $\theta_i = f(x_i;\gamma)$ maps a vector $x_i = (x_i^1, \ldots, x_i^k)$ of k observable characteristics for firm i into the unit interval. Suppose that the function $f(\cdot)$ is known up to a parameter vector γ. Substituting $\hat{q}_i = \theta_i \bar{Q}$ into the risk minimization program (4) yields

$$\min_{\gamma \in \Gamma} \sum_{i=1}^{n} r_i \left(f(x_i;\gamma)\bar{Q} \right) \text{ s.t. } \sum_{i=1}^{n} f(x_i;\gamma) = 1 \wedge f(x_i;\gamma) \geq 0 \quad \forall i. \tag{10}$$

[36]In a companion paper, we consider straightforward improvements to the current compensation scheme and quantify their implications for revenue raised in permit auctions (Martin et al., 2013a).

As this can be seen as a constrained version of (4), we refer to its solution as the "feasible optimal allocation". We specify an allocation rule based on the Cobb-Douglas function, $f(x_i;\gamma) = \frac{\prod_k (x_i^k)^{\gamma_k}}{\sum_{j=1}^n \prod_k (x_j^k)^{\gamma_k}}$, which generalizes e.g. grandfathering of historic emissions e_i (that is, $f(e_i;\gamma) = \frac{e_i^{\gamma_e}}{\sum_j e_j^{\gamma_e}}$ and $\gamma_e = 1$) to the case of multiple variables. We solve for γ using a standard maximum likelihood solver where $r_i\left(f(x_i;\gamma)\bar{Q}\right)$ corresponds to the likelihood contribution of observation i.

Table 6 reports the solution vector $\hat{\gamma}$ for x-vectors of varying lengths (panel A) along with the associated risk of job loss and carbon leakage (panel B). We hold $\bar{Q}$ fixed at the total amount of permits allocated for free during phase III; i.e. $\bar{Q} = \sum_i q_i^b$, where q_i^b is the average annual amount of free permits received by firm i under the benchmarking rules. As above, we minimize relocation risk either in terms of jobs or carbon emissions. We start by including only q_i^b in x_i, as an alternative way of assessing the efficiency of free allocation in phase III. If q_i^b is optimal, we should find that $\hat{\gamma}_b = 1$. If $\gamma_b < 1$, risk can be reduced by shifting permits from firms that receive more permits to those that receive less, and vice versa if $\gamma_b > 1$. When minimizing job risk, we obtain a point estimate of $\hat{\gamma}_b = 0.44$, which is smaller than 1 at the 5% significance level and corroborates our earlier finding that the benchmarking allocations induce too much job risk. In fact, the feasible optimal allocation reported in column 1 reduces job risk by 1.4 percentage points.

Next, we examine three allocation rules based on different combinations of observable characteristics. For instance, when using historic CO_2 emissions and employment size of a firm, the job risk drops by 2.3 percentage points (in column 2). This reduction is significant and closes 58% of the gap to the unconstrained minimum of 2.9% of all jobs in EU ETS firms.[37] Compared to column 1, the additional risk reduction is brought about by considering not only the firm's past CO_2 emissions but also employment, albeit with a smaller weight. Adding sector characteristics, such as carbon intensity and trade intensity with less developed countries, to the allocation function results in a small additional reduction of job risk, although the difference is not statistically significant.[38] Finally, measuring firm size in terms

[37] Panel B reports a reduction by at least 0.7 percent of EU ETS employment in 95 out of 100 bootstrap replications.

[38] We use TI with less developed countries because we find it to be more correlated with the VS

Table 6: Feasible optimal allocation rules

	(1)	(2)	(3)	(4)	(5)	(6)
	Minimizing expected job loss				Minimizing expected carbon leakage	
A. Parameter estimates $\hat{\gamma}$						
Benchmarking allocation	0.44 [0.23, 0.94]				1.13 [0.83, 1.27]	
CO_2 emissions		0.63 [0.51, 0.85]	0.58 [0.39, 0.78]	0.63 [0.50, 0.82]		1.02 [0.85, 2.66]
Employment		0.23 [0.11, 0.40]	0.29 [0.12, 0.57]			-0.20 [-0.98, -0.03]
Turnover				0.20 [0.11, 0.33]		
Carbon intensity			0.21 [-0.03, 0.53]			
Trade intensity w/ less developed			-0.05 [-0.11, 0.46]			
B. Minimized risk and change to Benchmarking allocation (in % of total ETS employment or emissions)						
Job risk	5.54 [9.05]	4.61 [7.14]	4.51 [6.73]	4.58 [7.29]	8.21 [12.08]	9.14 [15.51]
Δ	-1.39 [-0.09]	-2.31 [-0.74]	-2.41 [-0.88]	-2.35 [-0.73]	1.28 [2.71]	2.22 [7.09]
CO_2 risk	29.66 [39.53]	26.73 [37.61]	26.05 [35.50]	25.43 [36.14]	22.12 [32.33]	23.22 [31.78]
Δ	6.88 [13.17]	3.94 [8.86]	3.27 [8.25]	2.64 [8.00]	-0.67 [-0.01]	0.44 [4.19]

Notes: The sample consists of all 344 EU ETS firms we interviewed and for which we could match data on the phase III allocation, employment, turnover and CO_2 emissions. Panel A reports the parameters of the optimal feasible allocation rule for different vectors of observable variables. Panel B reports the associated risk of employment loss (in % of employment at all firms in the sample) and leakage (in % of CO_2 at all firms in the sample). The change is computed as the difference between minimal risk and the risk induced by the EU Benchmark Allocation. The optimality criterion is either job loss (columns 1 to 4) or carbon leakage (columns 5 and 6). Carbon intensity and trade intensity with less developed countries (TI less) are defined at the 4-digit industry level. The numbers in brackets report two-sided 95% confidence intervals of the coefficient estimates in Panel A and the 95th percentiles of the risk statistic in Panel B, obtained from a bootstrap with 100 replications.

of turnover rather than employment (in column 4) yields results virtually identical to those in column 2.

Feasible optimal allocation rules for minimizing CO_2 risk are reported in columns 5 and 6. Including only the EU benchmark allocation yields a parameter estimate $\hat{\gamma}_b$ which is not significantly different from unity. This is in line with the earlier finding that we cannot significantly reduce risk compared to the benchmark allocation. The same conclusion arises in column 6 where we include firm level employment and

than the overall TI used by the Commission. See Martin et al. (2013a) for an in-depth discussion of these correlations.

CO_2 in the allocation function.[39]

Two important lessons emerge from the feasible approach to optimal permit allocation. First, a simple allocation rule based on easily observable firm level variables performs at least as well as the benchmarking allocation, which is based on an elaborate – and presumably much more costly – administrative and political process. Second, feasible allocation rules based on both past emissions and firm size significantly reduce job risk, but have no significant impact on CO_2 risk. This suggests that there is scope for consensus between different stakeholders concerned with different types of relocation risk.

5 Conclusion

When governments intervene in markets to regulate negative externalities, industry associations often demand compensation for the adverse impact of regulation on their international competitiveness. If firms are to carry the full burden of regulation, so the argument goes, they have no choice but to relocate to an unregulated jurisdiction. From the government's perspective, relocation is undesirable because firms take with them jobs, taxable profits and – in the case of climate policy – the very emissions targeted by the regulation. We have proposed an industry compensation scheme aimed at minimizing the expected damage of such extensive-margin responses to regulation. This simple economic criterion requires that compensation be distributed across firms so as to equalize the expected marginal impact of relocation on the regulator's objective function.

We have applied this idea in the context of the EU ETS, where industry compensation is given in the form of free permit allocations, with the stated objective to prevent relocation and carbon leakage. Our analysis has shown that the criteria adopted by the EC to establish the risk of carbon leakage give rise to inefficient allocations. Optimal allocation yields drastic reductions in job risk, and so do simple approximations to the optimal allocation based on easily observable firm characteristics. Conversely, aggregate relocation risk induced by current compensation rules

[39] We do not find a significant reduction of CO_2 risk when including trade and carbon intensity as in column 3, either. These results are available on request.

could be maintained while handing out far less permits for free and selling more of them in permit auctions. This would generate additional auction revenue at a social cost much lower than that of alternative ways of raising public funds.

Our numerical analysis takes the EU's stated objective to prevent relocation and carbon leakage at face value. The benefit of this normative approach is that it highlights exactly how and by how much the implemented allocation rules deviate from a precisely-defined policy goal. This benefit extends beyond the European policy context, as similar compensation principles have been adopted by other carbon trading schemes worldwide. It stands to reason, however, that 'unofficial' policy objectives behind the free allocation scheme were more nuanced. For instance, free allocation is often used to build political support among large polluters in the initial stages of a cap-and-trade program. Future research could address these factors in the framework of a positive analysis of distributional aspects and the political economy of free permit allocation. Such an analysis might also take into account possible benefits of relocation, such as a reduction in subsidy payments or in local pollution levels.

The compensation principle proposed here also motivates further research into firms' relocation propensities under different allocation rules. This research could follow a variety of approaches, ranging from the econometric analysis of observed exit patterns to the design of a mechanism that implements optimal compensation. Finally, our approach can be employed to assess existing compensation schemes – or to design more efficient ones – in other settings where regulation increases the chance of an undesirable relocation of the regulated industry.

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Appendix (For Online Publication)

A Background on the management interviews

A.1 Interview practice

Interviews were carried out by graduate and postgraduate students after they had been trained. The interviewers were paid according to the number of interviews conducted, encouraging them to do more interviews and discouraging any firm background research, thus preserving the double-blind nature of the survey. Interviewers made "cold calls" to production facilities (not head offices), gave their name and affiliation and then asked to be put through to the production or environmental manager. In the case of EU ETS firms, interviewers requested to speak to the person responsible for the EU ETS. At this stage, the terms "survey" and "research" were avoided as both are associated with commercial market research and some switchboard operators have instructions to reject such calls. Instead, we told them that we were doing "a piece of work" on climate change policies and their impact on competitiveness in the business sector and would like to have a conversation with the manager best informed.

Once the manager was on the phone, the interviewer asked whether s/he would be willing to have a conversation of about 40-45 minutes about these issues. Depending on the manager's willingness and availability to do so, an interview was scheduled. If the manager refused, s/he was asked to provide the interviewer with another knowledgeable contact at the firm who might be willing to comment. Managers who agreed to give an interview were sent an email with a letter in PDF format to confirm the date and time of the interview and to provide background information and assure them of confidentiality. A similar letter was sent to managers who requested additional information before scheduling an interview.

All interviewers worked on computers with an internet connection and used VOIP software to conduct the interviews. They accessed a central interview database via a custom-built, secure web interface which included a scheduling tool and the interview application which displayed the questions along with the scoring grid. The interview screen contained hyperlinks to a manual with background information on each question. Interviewers scored answers during the interview. For all interviews, the scheduling history as well as the exact time and date, duration, identity of interviewer, etc. were recorded. All interviews were conducted in the language of the interviewee's residence.

The interview format follows the design pioneered by Bloom and van Reenen

Table A.1: Interview response rates by country

	# of Interviews	# of Firms Interviewed	# of ETS Firms Interviewed	# of Non ETS Firms Interviewed	Total Firms Contacted	Refused	Response Rate
Belgium	134	131	85	46	178	47	0.74
France	141	140	92	48	238	98	0.59
Germany	139	138	95	43	337	199	0.41
Hungary	69	69	37	32	90	21	0.77
Poland	78	78	57	21	140	62	0.56
UK	209	205	63	142	468	264	0.44
Total	770	761	429	332	1451	691	0.52

Notes: There are more interviews than interviewed firms as we conducted several interviews with different partners in a small number of firms.

(2007). This approach seeks to minimize cognitive bias by asking open-ended questions and by delegating the task of scoring the answers to the interviewer. In addition, a large sample size and interviewer rotation is exploited to control for possible bias on the part of the interviewers by including interviewer fixed effects in regression analyses. For further details, see Bloom and van Reenen (2010).

A.2 Sample characteristics

Table A.1 provides an overview of the number of interviews and the response rates broken down by country and by EU ETS participation status.[1] The last column shows the response rate i.e. the fraction of firms that were contacted and with whom we successfully conducted an interview. These vary somewhat between different countries. For example, it is particularly low in Germany (38%) and the UK (40%), whereas in Belgium or Hungary, firms were more willing to participate (74% and 78%, respectively). Generally, these figures are very high compared to response rates achieved in postal or online surveys.

It is important for the validity of our analysis to rule out possible selection bias in our sample. EU ETS firms are different from non-ETS firms, but within these two categories, interviewed firms are not significantly different from non-interviewed firms in regards to the most common characteristics available in ORBIS. This is shown in Panel A of Table A.2 where each of the principal firm characteristics available from the ORBIS database (turnover, employment and capital) is regressed on

[1] All analysts would first conduct interviews in the UK and only then go on to conduct interviews in another country allowing a common reference, hence the larger number of interviews for this country. This allows us to control for interviewer bias as discussed below and also for UK responses to be used as a benchmark.

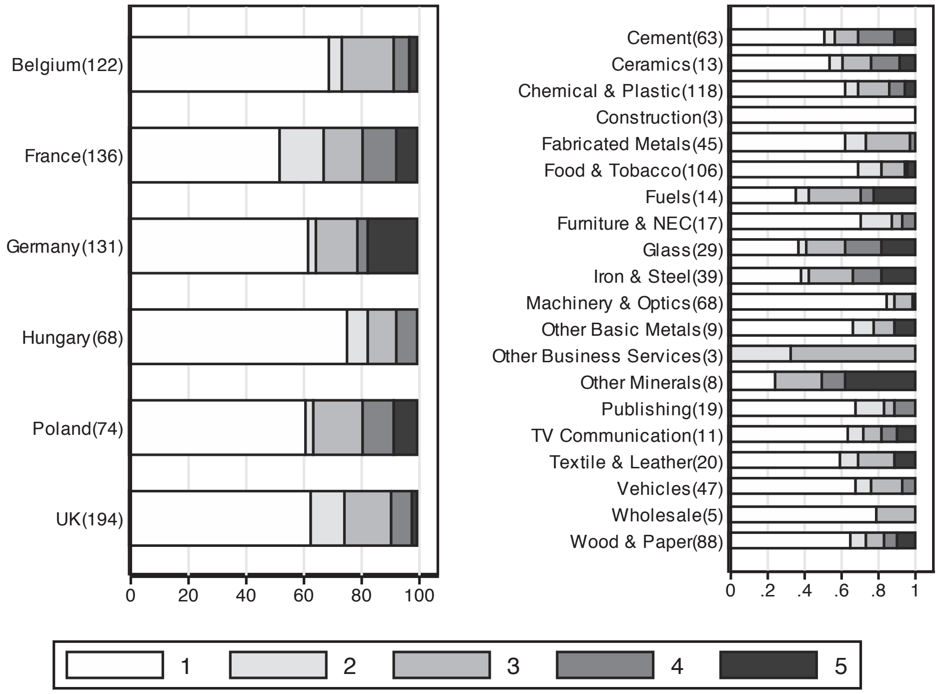
Table A.2: Sample representativeness

	(1) Turnover	(2) Employment	(3) Capital
A. All firms			
Firm contacted	-0.0322	-0.0794	0.172
	(0.0786)	(0.0611)	(0.108)
EU ETS firm	2.031***	1.452***	2.530***
	(0.095)	(0.080)	(0.145)
Number of observations	118,874	107,830	113,771
Number of firms	12,322	12,921	118,874
R-squared	0.511	0.364	12322
B. Contacted firms			
Firm granted interview	-0.0983	-0.0373	0.0443
	(0.118)	(0.0957)	(0.150)
EU ETS firm	2.044***	1.547***	2.540***
	(0.124)	(0.107)	(0.160)
Number of observations	26,114	23,933	25,815
Number of firms	1,373	1,420	1,297
R-squared	0.659	0.589	0.618

Notes: Regressions in panel A are based on the set of manufacturing firms with more than 50 employees contained in ORBIS for the six countries covered by the survey. Each column shows the results from a regression of the ORBIS variable given in the column head on a dummy variable indicating whether a firm was contacted or not and a dummy variable indicating whether a firm was taking part in the EU ETS at the time of the interviewing. Panel B shows analogous regressions for the set of contacted companies and with an indicator for whether an interview was granted. All regressions are by OLS and include country dummies, year dummies and 3-digit sector dummies. Standard errors are clustered at the firm level and are robust to heteroskedasticity and autocorrelation of unknown form.* significant at 10%; ** significant at 5%; *** significant at 1%.

a dummy variable indicating that a firm is part of the EU ETS, a dummy indicating that a firm was contacted, and a full set of sector and year dummies, with the result that the estimated coefficients are small and statistically insignificant. For the set of firms that either conceded or refused an interview, we ran analogous regressions to estimate an intercept specific to firms that granted us an interview. The results in Panel B of Table A.2 show that none of these intercepts is statistically significant. We thus conclude that our sample is representative of the underlying population of medium-sized manufacturing firms in the six European countries covered by our study.

Figure A.1: Distribution of vulnerability score by country and industry



Notes: Bar charts show the distribution of the vulnerability score by country (left) and by 3-digit NACE sector (right). The score ranges from 1 (no impact) to 5 (complete relocation). A score of 3 is given if at least 10% of production or employment would be outsourced in response to future carbon pricing. The number of observations in each country and industry is given in parenthesis. NEC: Not elsewhere classified.

Table A.3: Firm characteristics by ETS participation status

	ETS Firms			non ETS Firms		
	Mean	Std. Dev.	Obs.	Mean	Std. Dev.	Obs.
Firm						
Age (years) *	40	37	409	33	37	327
Turnover (EUR million) **	725.73	3,611.50	398	146.42	767.93	298
Number of employees **	1,418	5,092	394	469	857	305
EBIT (EUR million) **	26.12	100.54	391	5.22	23.47	292
Number of shareholders	2	5	429	3	5	332
Number of subsidiaries	6	32	429	2	5	332
Firm's Global Ultimate Owner						
Turnover (USD million)	31,695	67,080	142	12,464	21,980	99
Number of employees	50,012	71,864	131	42,381	73,834	95

Notes: Based on 2007 data. Stars next to a variable name indicate that the respective means for ETS and non ETS firms are significantly different at the 10% (*), 5% (**), and 1% (***) levels.

B Robustness of vulnerability score

B.1 External consistency: Energy price regressions

We compile data on firm-level employment, wages and energy prices in European and OECD countries for the years from 1999 until 2007. Table B.1 summarizes the data.

Employment Our sample covers all firms contained in the ORBIS database which have 10 or more employees in at least one year during the sample period. In addition to employment, this source also provides industry codes at the 3-digit NACE level. The EU sample includes Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden and the United Kingdom. In addition to those countries, the OECD sample includes Canada, Mexico, Japan, Switzerland, and the United States of America, but not Romania.

Energy prices Price data for electricity, gas, liquid and solid fuels comes from the 'Energy Prices and Taxes database' maintained by the International Energy Agency.[2] To ensure comparability of prices across fuels, we adjust for net calorific value using prices in US$ per ton of oil equivalent (TOE). For each country c and

[2] International Energy Agency (2009). Energy Prices and Taxes. Quarter 3. Paris, France.

Table A.4: Descriptive statistics of the vulnerability score

	Mean	Standard deviation	Min	P25	Median	P75	Max	Firms
Overall vulnerability score	1.87	1.29	1	1	1	3	5	725
A. by country								
Belgium	1.69	1.13	1	1	1	3	5	122
France	2.07	1.34	1	1	1	3	5	136
Germany	2.12	1.58	1	1	1	3	5	131
Hungary	1.50	0.95	1	1	1	2	4	68
Poland	2.03	1.40	1	1	1	3	5	74
UK	1.75	1.12	1	1	1	3	5	194
B. by 3-digit sector								
Cement	2.33	1.52	1	1	1	4	5	63
Ceramics	2.15	1.46	1	1	1	3	5	13
Chemical & Plastic	1.86	1.26	1	1	1	3	5	118
Construction	1.00	0.00	1	1	1	1	1	3
Fabricated Metals	1.67	0.93	1	1	1	3	4	45
Food & Tobacco	1.56	1.01	1	1	1	2	5	106
Fuels	2.71	1.59	1	1	3	4	5	14
Furniture & NEC	1.47	0.87	1	1	1	2	4	17
Glass	2.76	1.57	1	1	3	4	5	29
Iron & Steel	2.69	1.56	1	1	3	4	5	39
Machinery & Optics	1.26	0.68	1	1	1	1	4	68
Other Basic Metals	1.78	1.39	1	1	1	2	5	9
Other Business Services	2.67	0.58	2	2	3	3	3	3
Other Minerals	3.38	1.69	1	2	4	5	5	8
Publishing	1.58	1.02	1	1	1	2	4	19
TV Communication	1.91	1.45	1	1	1	3	5	11
Textile & Leather	1.90	1.33	1	1	1	3	5	20
Vehicles	1.62	0.99	1	1	1	2	4	47
Wholesale	1.40	0.89	1	1	1	1	3	5
Wood & Paper	1.85	1.36	1	1	1	3	5	88

Notes: Summary statistics of the overall vulnerability score (first row), by country (panel A) and by 3-digit NACE sector (panel B). The score ranges from 1 (no impact) to 5 (complete relocation). A score of 3 is given if at least 10% of production of employment would be outsourced in response to future carbon pricing. NEC: Not elsewhere classified.

Table A.5: Differences in vulnerability score by sector and country

	(1)	(2)
	Deviations from the overall mean	
A. Countries		
Belgium	-0.034	0.054
France	0.361 **	0.322 *
Germany	0.032	0.021
Hungary	-0.402 *	-0.378
Poland	0.311	0.013
United Kingdom	-0.269	-0.032
3-digit Sector controls	no	yes
B. Sectors		
Ceramics	-0.011	-0.010
Cement	0.379 **	0.382 **
Chemical & Plastic	-0.168	-0.171
Fabricated Metals	-0.268 *	-0.272 *
Food & Tobacco	-0.474 ***	-0.474 ***
Fuels	0.563	0.566
Furniture & NEC	-0.584 ***	-0.583 ***
Glass	0.752 ***	0.752 ***
Iron & Steel	0.703 ***	0.697 ***
Machinery & Optics	-0.731 ***	-0.733 ***
Other Basic Metals	-0.284 **	-0.287
Other Minerals	1.278 **	1.285 **
Publishing	-0.415 *	-0.413 *
Textile & Leather	-0.130	-0.125
TV & Communication	-0.028	-0.025
Vehicles	-0.434 ***	-0.447 ***
Wood & Paper	-0.149	-0.147
Employment control	no	yes
Observations	725	725

Notes: Reported coefficients represent the deviation of a country/sector's intercept from the overall mean vulnerability score. Panel A is based on a regression of the vulnerability score on country dummies with additional controls for interview noise and 3-digit sector (column 2). Panel B is based on a regression of the vulnerability score on broadly defined sector dummies with additional controls for interview noise and employment (column 2). The asterisks indicate statistical significance of a t-test of equality of the country/sector's intercept and the overall mean (* p<0.1, ** p<0.5, *** p<0.01). NEC: Not elsewhere classified.

Table B.1: Descriptive statistics: Employment, energy prices and wages

	Mean	Standard deviation	Min	P25	Median	P75	Max
A. OECD							
Employment	120	542	1	20	39	93	86,607
log(employment)	3.87	1.14	0.00	3.00	3.66	4.53	11.37
Δlog(employment)	0.01	0.23	-1.99	-0.05	0.00	0.06	2.00
Domestic EP index [EP^D]	6.28	0.47	4.87	5.92	6.27	6.64	7.84
Foreign EP index [EP^F]	6.15	0.31	5.17	5.93	6.15	6.38	7.10
Relative energy price [EP^D-EP^F]	0.13	0.36	-0.73	-0.16	-0.01	0.50	1.05
ΔRelative energy price	0.00	0.08	-0.30	-0.06	-0.01	0.05	0.49
Domestic wage index [W^D]	0.00	0.08	-0.50	-0.05	0.00	0.04	5.19
Foreign wage index [W^F]	0.03	0.14	-0.28	-0.06	0.04	0.10	0.68
Relative wage [$Wage^D$-$Wage^F$]	-0.03	0.14	-0.81	-0.05	-0.02	0.03	5.36
ΔRelative wage	-0.02	0.13	-4.69	-0.04	-0.02	0.00	0.72
Firms: 113,680 (Observations: 464,272)							
B. Europe							
Employment	117	546	1	19	37	86	86,607
log(employment)	3.81	1.15	0.00	2.94	3.61	4.45	11.37
Δlog(employment)	0.01	0.24	-1.99	-0.05	0.00	0.07	2.00
Domestic EP index [EP^D]	6.23	0.47	4.87	5.89	6.17	6.52	7.84
Foreign EP index [EP^F]	6.14	0.31	5.17	5.92	6.14	6.37	7.10
Relative energy price [EP^D-EP^F]	0.09	0.36	-0.73	-0.17	-0.04	0.41	1.05
ΔRelative energy price	0.02	0.08	-0.30	-0.04	0.00	0.07	0.49
Domestic wage index [W^D]	0.00	0.09	-0.65	-0.05	0.00	0.05	5.19
Foreign wage index [W^F]	0.03	0.15	-0.27	-0.06	0.04	0.10	0.68
Relative wage [$Wage^D$-$Wage^F$]	-0.03	0.15	-0.81	-0.04	-0.02	0.03	5.36
ΔRelative wage	-0.01	0.14	-4.69	-0.03	-0.02	0.00	0.72
Firms: 94,398 (Observations: 396,182)							

Notes: The sectoral energy price (EP^D) is the average of the logarithmic prices of different fuel categories, weighted by the sector's expenditure shares for each category in the UK in 2004. The domestic wage index is the logarithmic change in the wage against its level in 2004. Foreign EP and wage indices are the averages of all foreign EP and wage variables, respectively, inversely weighted by the geographical distance to the foreign country. Δ stands for the first time difference (t-(t-1)) of a variable.

year t, we compute the energy price in sector s as

$$EP_{cst}^{D} = \left(\sum_{e} \omega_s^e ln(p_{ct}^e) \right) \tag{B.1}$$

where p_{ct}^e is the price of fuel $e \in$ {electricity, gas, liquid fuel, solid fuel} and ω_s^e is the expenditure share of fuel e in sector s. Since expenditure shares are not available for all countries in the sample, we impute them using UK data at the 3-digit NACE code taken from the Quarterly Fuels Inquiry data maintained by the UK Office for National Statistics. We hold these shares fixed at their 2004 values – the latest year for which we have this information – in order to avoid the issue of endogenous changes in fuel expenditures.

In order to account for energy price variation in the other countries, we calculate a sectoral index of foreign energy prices as the average of the energy price indices (EP^D) in all countries j other than c, inversely weighted by their geographical distance d_{cj} to country c:

$$EP^F_{cst} = \sum_{j \neq c} EP^D_{jst} \left(\frac{d^{-1}_{cj}}{\sum_{k \neq c} d^{-1}_{ck}} \right) \tag{B.2}$$

Finally, we define the energy price differential between home and foreign countries as

$$\widetilde{EP}_{cst} \equiv EP^D_{cst} - EP^F_{cst} \tag{B.3}$$

Wages Wages at the 2-digit industry level, W_{cst}, are taken from the LABORSTA database maintained by the International Labour Organization (see http://laborsta.ilo.org). Note that wage data are reported on different scales (e.g. monthly, hourly) by the different sectors. This is however not an issue as we take the logarithmic measure of wages and control for sectoral trends in the regressions. We construct an index of foreign wages for each country c and sector s in year t as

$$W^F_{cst} = \sum_{j \neq c} \ln W_{jst} \left(\frac{d^{-1}_{cj}}{\sum_{k \neq c} d^{-1}_{ck}} \right) \tag{B.4}$$

and define the difference between local and foreign wages as

$$\widetilde{W}_{cst} \equiv W^D_{cst} - W^F_{cst}. \tag{B.5}$$

Vulnerable sectors We want to assess the ability of the VS measure to identify firms that are at risk of relocation. Since we do not have firm-level VS for the entire ORBIS sample, we compute the employment-weighted average VS for each (3-digit level) sector in the interview sample. We examine the relationship between VS and the price elasticities of employment using 3 types of interactions. Firstly, we interact the price variables (energy and wages) with an above-median indicator variable ($\mathbb{I}\{VS_s > q(50)\}$). This group is referred to as "High VS". Secondly, we interact the price variables with the deviation from the mean VS ($VS_s - \bar{VS}$). Finally, we re-estimate the first specification but interact the price variables also with indicators of the second and fourth quartiles of the VS distribution, i.e. $\mathbb{I}\{q(25) < VS_s < q(50)\}$ and $\mathbb{I}\{q(75) < VS_s\}$. The coefficients on these variables tell us if price elasticities of employment vary significantly between the quartiles on either side of the median.

Table B.2: Dynamic Panel Regressions of (log) employment

	(1)	(2)	(3)	(4)	(5)	(6)
	Employment					
	OECD			European Union		
Employment$_{t-1}$	0.966***	0.966***	0.966***	0.950***	0.949***	0.950***
	(0.006)	(0.006)	(0.006)	(0.007)	(0.007)	(0.006)
Relative energy price [EP^D-EP^F]	0.046***	0.038**	0.040**	0.089***	0.072***	0.080***
	(0.018)	(0.018)	(0.017)	(0.016)	(0.016)	(0.016)
× High VS [3rd & 4th VS quartiles]	-0.019***		-0.017***	-0.026***		-0.025***
	(0.004)		(0.005)	(0.004)		(0.005)
× VS-mean(VS)		-0.007***			-0.009***	
		(0.002)			(0.002)	
× 2nd VS quartile			-0.008			-0.006
			(0.006)			(0.006)
× 4th VS quartile			-0.006			-0.002
			(0.005)			(0.005)
Relative wage (W^D-W^F)	-0.022***	-0.022***	-0.021***	-0.012**	-0.012**	-0.012**
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
× High VS [3rd & 4th VS quartiles]	-0.001**		0.001	0.003		0.009***
	(0.000)		(0.001)	(0.002)		(0.003)
× (VS-mean(VS))		-0.001***			-0.001	
		(0.000)			(0.001)	
× 2nd VS quartile			-0.001			-0.003
			(0.001)			(0.003)
× 4th VS quartile			-0.003***			-0.012***
			(0.001)			(0.002)
Country-by-year effects	yes	yes	yes	yes	yes	yes
Sector trends	yes	yes	yes	yes	yes	yes
Firms	113,680	113,680	113,680	94,398	94,398	94,398
Observations	464,272	464,272	464,272	396,182	396,182	396,182

Notes: The dependent variable is the firm employment measured on a logarithmic scale. The vulnerability score (VS) is the sectoral employment-weighted vulnerability score, and the quartiles are defined on the panel sample. All regressions are implemented with the System GMM by Blundell and Bond which includes a level and a differenced equation with lagged differences and twice-lagged levels of the endogenous variables as instruments. Robust standard errors, clustered at the firm level, are in parentheses. Asterisks indicate statistical significance at the 10%(*), 5%(**) and 1%(***) level.

Estimation We estimate equations of the form

$$\begin{aligned} l_{isct} &= \beta_l l_{isct-1} + \beta_P \widetilde{EP}_{sct-1} + \beta_W \widetilde{W}_{sct-1} \\ &\quad + \sum_{X \in \mathbb{X}} X_s \left(\beta_{XP} \widetilde{EP}_{sct-1} + \beta_{XW} \widetilde{W}_{sct-1} \right) \\ &\quad + \alpha_{ct} + \alpha_{st} t + \alpha_i + \varepsilon_{it} \end{aligned} \tag{B.6}$$

where l is the logarithmic employment, $\mathbb{X}$ contains different sets of variables derived from the sectoral VS,[3] α_{ct} is a country-by-year effect, α_{st} captures a sector specific trend and α_i is a firm fixed effect. Following Blundell and Bond (1998), we estimate a system of equation (B.6) in levels and first differences with differences of the explanatory variables and lagged levels, respectively, as instruments. The system GMM estimator is necessary in our case as its less restrictive alternative, the Arellano-Bond estimator, is susceptible to a severe weak instrument bias given the high auto-correlation coefficient β_l that we find below. In Table B.3 we also report OLS estimates of equation (B.6) (i.e. abstracting from firm fixed effects) which leaves our key qualitative results on energy prices intact.

In addition to the energy price elasticities reported in Table 2 in the main text, Table B.2 reports the coefficients on wages as well as an additional specification in columns 3 and 6 where we interact the price coefficients with four VS quartile band indicators. The effects of energy prices in the second and fourth quartiles are not statistically significant, which supports the more parsimonious specification with the High VS dummy that we report in main text.

In all specifications, employment responds negatively to an increase in relative wages, which is in line with expectations. There is some evidence of negative interactions with the VS measures, yet the pattern is less robust than the one found for energy prices. For the EU sample, for instance, we find a non-monotone relationship in column 6 where the third quartile is less responsive than the fourth quartile. Of course there is no reason why we should expect a particular pattern for wages in terms of VS. Finally, the OLS estimates of energy prices elasticities reported in Table B.3 lead to comparable results, although the coefficients on the endogenous wage variable naturally look less plausible.

[3] In the first specification, $\mathbb{X} = \{\mathbb{I}\{q(50) < VS_s\}\} = High\,VS$, in the second specification $\mathbb{X} = \{VS - mean(VS)\}$, and in the last specification $\mathbb{X} = \{\mathbb{I}\{q(50) < VS_s < q(100)\}, \mathbb{I}\{q(25) < VS_s < q(50)\}, \mathbb{I}\{q(75) < VS_s\}\}$.

Table B.3: OLS Regressions of (log) employment

	(1)	(2)	(3)	(4)	(5)	(6)
	Employment					
	OECD			European Union		
$Employment_{t-1}$	0.973***	0.973***	0.973***	0.970***	0.970***	0.970***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Relative energy price [EP^D-EP^F]	0.017***	0.009*	0.015***	0.008	0.000	0.007
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.006)
× High VS [3rd & 4th VS quartiles]	-0.010***		-0.006**	-0.011***		-0.008***
	(0.002)		(0.003)	(0.002)		(0.003)
× VS-mean(VS)		-0.004***			-0.005***	
		(0.001)			(0.001)	
× 2nd VS quartile			0.010**			0.007*
			(0.004)			(0.004)
× 4th VS quartile			-0.005			-0.005
			(0.003)			(0.003)
Relative wage (W^D-W^F)	0.000	0.000	0.001	0.006**	0.006**	0.007**
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
× High VS [3rd & 4th VS quartiles]	-0.001***		-0.000	-0.000		-0.001**
	(0.000)		(0.000)	(0.001)		(0.001)
× (VS-mean(VS))		-0.001***			-0.000	
		(0.000)			(0.000)	
× 2nd VS quartile			-0.002***			-0.002***
			(0.000)			(0.001)
× 4th VS quartile			-0.002***			0.000
			(0.000)			(0.001)
Country-by-year effects	yes	yes	yes	yes	yes	yes
Sector trends	yes	yes	yes	yes	yes	yes
Firms	113,680	113,680	113,680	94,398	94,398	94,398
Observations	464,272	464,272	464,272	396,182	396,182	396,182

Notes: The dependent variable is the firm employment measured on a logarithmic scale. The vulnerability score (VS) is the sectoral employment-weighted vulnerability score, and the quartiles are defined on the panel sample. All regressions are estimated by OLS. Robust standard errors, clustered at the firm level, are in parentheses. Asterisks indicate statistical significance at the 10%(*), 5%(**) and 1%(***) level.

B.2 Reliability of the vulnerability score: a regression discontinuity design

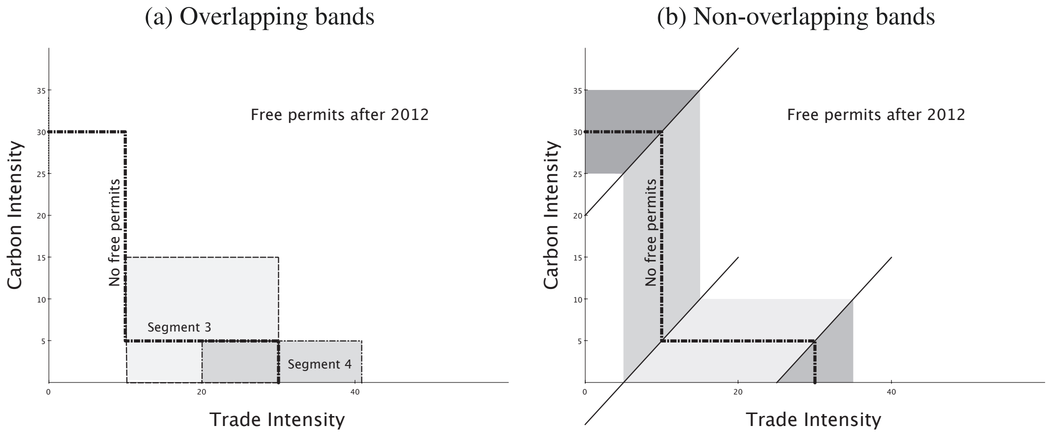
This section performs an additional test of the reliability of the vulnerability score (VS). The score is based on the interviewees' assessment of their reaction to carbon pricing policies until 2020, when assuming that they would not receive any permits for free. This is a counterfactual scenario because the manufacturing firms we interviewed could expect to receive part of their emission permits for free under the benchmarking rule, or receive even more permits for free if they were considered to be at risk of carbon leakage. The criteria and thresholds for determining carbon leakage risk were set out in Directive 2009/29/EC, published four months before we started the interviews. Therefore, we cannot rule out the possibility that some respondents correctly anticipated that they would receive free permits. Here we employ a regression discontinuity design (RDD) to test whether anticipation of free permit allocation influenced interview responses in spite of our request to consider the case of no free permits. As discussed in the main text, the criteria for free allocation were defined in terms of a number of thresholds for the sector's trade and carbon intensity. If the criteria were in fact known by the respondents and affected their reported VS, we should observe discrete jumps in VS around the relevant threshold values.

This test only has power if the sharp discontinuity in free permit allocation at the thresholds translated into a sharp discontinuity in managers' expectations. The data requirements for computing sector averages are not trivial (Juergens et al., 2013; EU Commission, 2009), and the first official list of sectors at risk was not published until after the interview process was completed (cf. Decision 2010/2/EU of 24 December 2009). If managers did hold expectations about free permit allocation but failed to predict on which side of the thresholds their sector was going to be, then the RDD based test proposed here might fail to reject for the wrong reason.

To guard against this possibility, we also test for discrete jumps in the score relating to the expected stringency (ES) of phase III of the EU ETS. This score, which is based on questions 9b)-9e) of the interview script reproduced in Appendix G, measures stringency not only in terms of the overall cap – which determines the permit price – but also in terms of how difficult it will be for the firm to keep emissions in check with the free permit allocation it expects to receive in the future. Since this latter aspect of stringency varies with free permit allocation, it also depends on the thresholds for carbon leakage sectors. Finding threshold effects for ES would thus strengthen the power of the RDD based test performed on the VS.

To begin, consider the four thresholds depicted by the bold line in panel (a) of Figure B.1. CI thresholds are at 30% (segment 1) and at 5% (segment 3), whilst thresholds for TI are at 10% (segment 2) and at 30% (segment 4). Most of the

Figure B.1: Defining threshold bands



firms in our sample are concentrated in segments 3 and 4. A traditional RDD can be employed to estimate the threshold effect in a narrow band around the threshold. For example, panel (a) ofFigure B.1 depicts 10% bands on either side of segments 3 and 4. Figure B.2 plots fitted regression lines and confidence bands on either side of the thresholds, for either of the two segments. Panels (a) and (c) of the figure focus on the 5% threshold for CI, and panels (b) and (d) on the 30% threshold for TI. In panels (c) and (d) of Figure B.2, the regression lines are restricted to have the same slope above and below the threshold. In neither case can we detect a significant discontinuity at the threshold. The point estimates of these threshold effects are small, positive and statistically insignificant. Had the interviewees factored their subsequent continued free allocation into their responses, we should have observed a negative and statistically significant effect. Interestingly, we do observe such an effect for the ES score. Panels (b) and (d) of Figure B.3 show a clear jump in the score value when the 30% trade intensity threshold is crossed.

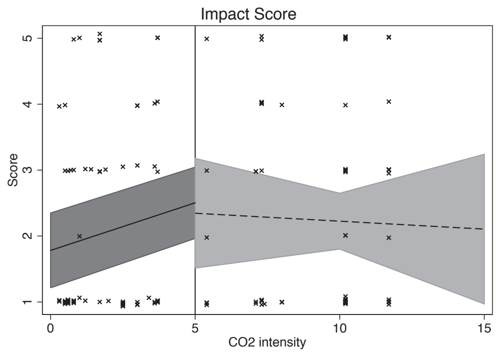
To account for multiple running variables and two-dimensional thresholds, we use an approach similar to Papay et al. (2011). First, we partition the sample along the four segments, as shown in panel (b) of Figure B.1. Next, we estimate the equation

$$VS_{ij} = \sum_{s=1}^{4} \mathbb{I}_{\{i \in \mathscr{F}_s(B)\}} \cdot \left(\beta^s_{CI} \cdot CI_j + \beta^s_{TI} \cdot TI_j\right) + \beta_D \cdot EXEMPT_j + \mathbf{x}'_{ij}\beta_x + \varepsilon_{ij} \quad \text{(B.7)}$$

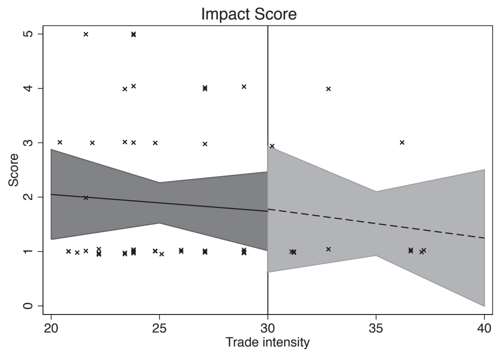
where s indexes the segment, $\mathscr{F}_s(B)$ denotes the set of firms i in sector j that fall into the band B around a particular segment, $\mathbb{I}\{\cdot\}$ is the indicator function and $\mathbf{x}_{ij}$

Figure B.2: Effect of exemption thresholds on VS? Graphical analysis

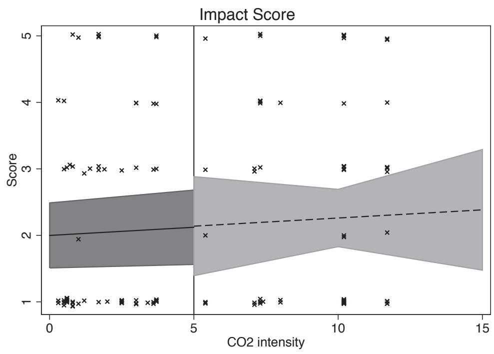
(a) 5% CI Threshold - 10% Bands



(b) 30% TI threshold - 10% Bands



(c) 5% CI threshold - 10% Bands - equal slopes



(d) 30% TI threshold - 10% Bands - equal slopes

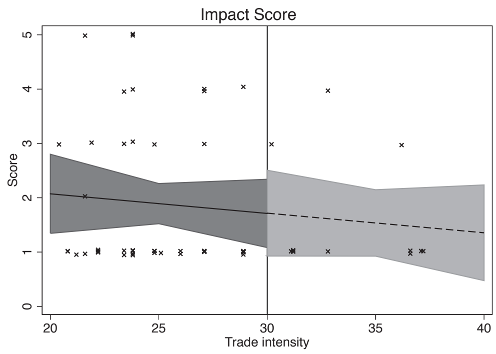
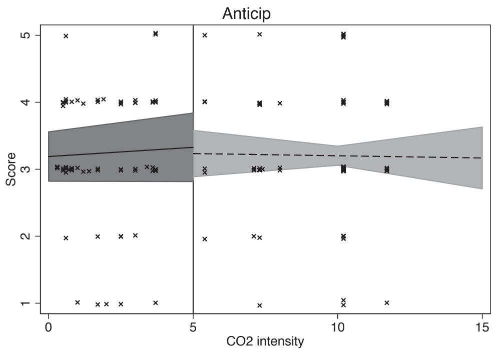
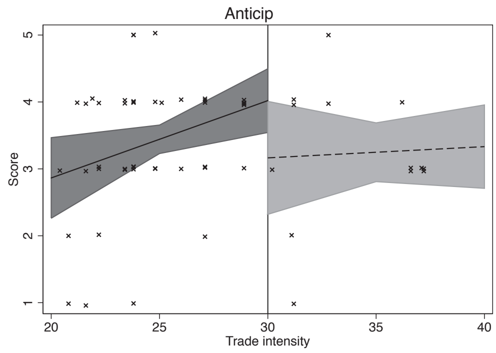


Figure B.3: Effect of exemption thresholds on expected stringency? Graphical analysis

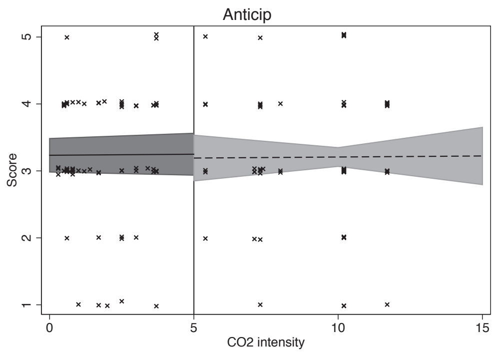
(a) 5% CI Threshold - 10% Bands



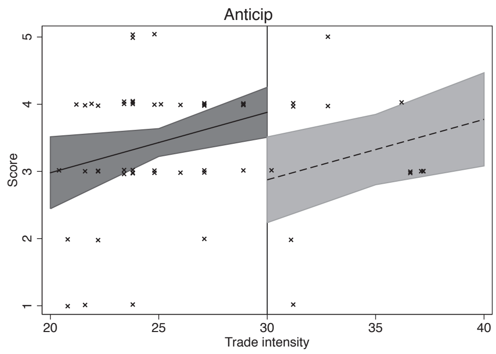
(b) 30% TI threshold - 10% Bands



(c) 5% CI threshold - 10% Bands - equal slopes



(d) 30% TI threshold - 10% Bands - equal slopes



is a vector of additional control variables.[4] $EXEMPT_j$ is a dummy variable indicating that sector j will receive free permits by virtue of being above the threshold. The threshold effect is identified across all partitions, using observations within a 10% band from each threshold. We allow for different coefficients on the running variables CI_j and TI_j underlying the threshold dummy D_j.

Panel A of Table B.4 summarizes the results. The baseline specification, which is linear in the running variables and lacks further controls, yields a statistically insignificant coefficient of 0.21 (in column 1). This means that firms just above the threshold for free permit allocation have a VS that is 0.21 points (about one tenth of the standard deviation in this sample) higher on average than the VS for firms just below the threshold. The specification in column 2 includes firm-level CO_2 emissions and employment as control variables, in addition to interview noise controls (i.e. interviewer dummies as well as interview and interviewee characteristics). The point estimate for the threshold effect becomes negative but remains insignificant and small in magnitude. Choosing narrower bands (5% on either side of the threshold) changes the threshold estimate very little, as reported in column 3. If anything, the point estimate is closer to 0. Columns 4 through 6 report the results when eq. (B.7) is estimated with 15% and 20% bands, or with a second-order polynomial in the running variables. Neither specification gives rise to a statistically significant threshold effect.

Panel B of Table B.4 reports results based on the same specifications, but using ES as the dependent variable. We find a significant negative threshold effect for all specifications, suggesting that a considerable number of firms had correct expectations about their future permit allocation situation. Since we do not find threshold effects on VS in spite of this, we conclude that managers understood correctly that their response to the question underlying the VS was conditional on not receiving free permits.

C Computational appendix

C.1 Firm level allocation

We implement the dynamic programming algorithm to solve programs (4) and (6) in a STATA ado file using MATA language. The structure of these programs is akin to a dynamic 'cake eating problem' Adda and Cooper (2003), with the difference that the 'cake' is not distributed over time but across firms. This approach can be

[4] We experiment with different specifications for the running variables (linear vs. quadratic) and controls, as well as with different bandwidths. They all yield similar results, as shown in Table B.4. Additional results are available from the authors upon request.

Table B.4: Effect of exemption thresholds on VS and ES? RDD estimates

	(1)	(2)	(3)	(4)	(5)	(6)
	A. Dependent Variable: Vulnerability Score (VS)					
EXEMPT	0.21	-0.23	-0.17	-0.22	-0.52	-0.37
	(0.256)	(0.314)	(0.376)	(0.331)	(0.515)	(0.479)
Log(employment)		-0.07	-0.08	-0.08	-0.09	-0.09
		(0.073)	(0.072)	(0.073)	(0.071)	(0.070)
Log(CO_2 emissions)		0.191**	0.199***	0.199**	0.206**	0.192**
		(0.078)	(0.076)	(0.078)	(0.079)	(0.077)
Multinational dummy		-0.23	-0.16	-0.23	-0.19	-0.17
		(0.176)	(0.181)	(0.173)	(0.178)	(0.174)
	B. Dependent Variable: Expected Stringency (ES)					
EXEMPT	-0.356*	-0.461**	-0.417*	-0.466**	-0.513**	-0.967***
	(0.191)	(0.191)	(0.221)	(0.189)	(0.226)	(0.284)
Log(employment)		-0.001	0.007	-0.001	0.010	0.009
		(0.038)	(0.038)	(0.038)	(0.037)	(0.042)
Log(CO_2 emissions)		0.148***	0.152***	0.146***	0.142***	0.133***
		(0.049)	(0.046)	(0.048)	(0.049)	(0.048)
Multinational dummy		0.293**	0.279**	0.293**	0.313**	0.317**
		(0.134)	(0.128)	(0.134)	(0.135)	(0.128)
Noise controls	no	yes	yes	yes	yes	yes
Observations	310	310	310	310	310	310
above thresholds in band	106	106	34	109	146	106
below thresholds in band	137	137	102	137	137	137
Bands	10%	10%	5%	15%	20%	10%
Running variables	Linear	Linear	Linear	Linear	Linear	Quadratic

applied to a broad class of specifications for the relocation probability and objective functions. Importantly, it allows us to solve the dual problem (6) as well.

Primal program: Minimize risk subject to fixed permit allocation Firm i's contribution to aggregate relocation risk is given by

$$r_i(q_i) = \frac{d_i}{1+\exp(\beta_{0i}+\beta_{1i}q_i)} \tag{C.1}$$

where d_i is the damage caused by relocation of firm i. This is substituted into the Bellman equation

$$V_i(s_i) = \min_{0\leq q_i\leq s_i} r_i(q_i) + V_{i+1}(s_i - q_i) \tag{C.2}$$

We evaluate eq. (C.1) for each firm on a grid ranging from 0 to $\bar{Q}$. This matrix is passed on to the program cake.ado which evaluates and solves (C.7).

Dual Program: Minimize free permit allocation subject to fixed risk. Since $F_i(-\pi_i(\cdot))$ is strictly monotonic in q_i we can invert eq. (C.1) to get

$$q_i = \pi_i^{-1}\left[-F_i^{-1}\left(\frac{r_i}{\alpha l_i + (1-\alpha)e_i}\right)\right]$$

and rewrite the dual program (6) as

$$\min_{\{r_i\geq 0\}} \sum_{i=1}^{n} \pi_i^{-1}\left[-F_i^{-1}\left(\frac{r_i}{\alpha l_i + (1-\alpha)e_i}\right)\right] \text{ s. t. } \left(\sum_i r_i \leq \bar{R}\right). \tag{C.3}$$

That is, rather than allocating the pieces of a fixed pie of free permits so as to reduce total risk, we now allocate the pieces of a fixed pie of relocation risk so as to minimize total permits. For all firms with $\beta_{1i} > 0$ we invert function (C.1) over the positive range to obtain

$$q_i(r_i) = \begin{cases} \frac{1}{\beta_{1i}}\log\left(\frac{d_i}{r_i}-1\right) - \frac{\beta_{0i}}{\beta_{1i}} & r_i < \frac{d_i}{1+\exp(\beta_{0i})} \\ 0 & \text{otherwise} \end{cases} \tag{C.4}$$

The corresponding Bellman equation is given by

$$W_i(s_i) = \min_{0\leq r_i\leq s_i} q_i(r_i) + W_{i+1}(s_i - r_i) \tag{C.5}$$

Again this function can be written as a vector on a grid and passed on to cake.ado which computes the minimum allocation.

C.2 Sector level allocation

In the sector-level allocation scenario, it is assumed that the regulator assigns free permits to the sector as a whole but refrains from redistributing emission permits amongst the firms in this sector. Denote by θ_{ij} $(0 \leq \theta_{ij} \leq 1)$ firm i's share in the total amount of permits Q_j allocated to sector j. We assume that firms receive emission permits in proportion to their historical emissions e_i, i.e. $\theta_{ij} = \frac{e_i}{\sum_{k \in j} e_k}$.

Primal program Sector j's contribution to aggregate risk of relocation is given by

$$R_j(Q_j) = \sum_{i \in j} \frac{d_i}{1 + \exp\left(\beta_{0i} + \beta_{1i}\theta_{ij}Q_j\right)}. \tag{C.6}$$

These can be vectorized and passed on to the cake.ado program to solve the Bellman equation

$$V_j\left(S_j\right) = \min_{0 \leq Q_j \leq S_j} R_j(Q_j) + V_{j+1}\left(S_j - Q_j\right). \tag{C.7}$$

The program returns the optimal quantities of free permits for each sector, and thanks to the shares θ_{ij} these map directly into firm level allocations.

Dual Program In order to use cake and the assumption of proportional permit allocation within sectors, one would have to invert the sector risk function (C.6). Since there is no closed-form solution for the inverse, we do not compute the permit minimizing sector-level allocation.

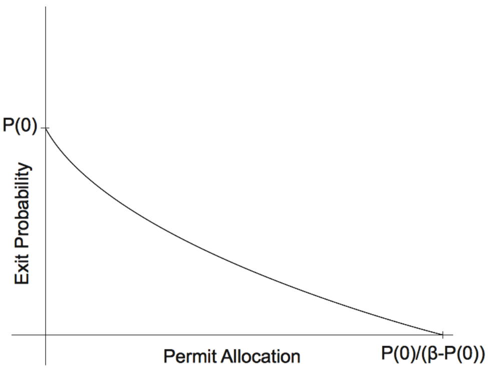
C.3 Further details on computation

Characteristics of the relocation probability The probability of exiting is a declining function of free permits q_i bounded between 0 and 1 (cf. Figure C.1). The marginal impact on firm exit of an additional unit of free permits for firm i is given by

$$\frac{dF_i\left[-\pi_i(q_i)\right]}{dq_i} = \beta_{1i} \frac{-\exp\left(\beta_{0i} + \beta_{1i}q_i\right)}{\left[1 + \exp\left(\beta_{0i} + \beta_{1i}q_i\right)\right]^2} \tag{C.8}$$

which is strictly negative for $\beta_{1i} > 0$. This is the case if allocating more permits for free strictly reduces the relocation probability, i.e. $F_i(0) > F_i(0.8e_i)$. Since the marginal impact of free permits on the relocation probability is declining in absolute value, the government should allocate free permits first to firms with the highest absolute impact of the first free permit, $\frac{\beta_{1i}\exp(\beta_{0i})}{[1+\exp(\beta_{0i})]^2}$.

Figure C.1: The shape of the exit probability function



Sample Out of 770 interviewed firms, there are 429 EU ETS firms. Of these we dropped firms with missing information on the survey questions, on the ORBIS variables, and on the phase III benchmark allocation. This leaves us with 344 observations across the six countries for the simulations.

Variables Employment l_i and turnover are calculated as pre-sample averages of the number of employees from ORBIS over the years from 2005 to 2008. CO_2 emissions, e_i, are caculated as the average of surrendered permits from CITL in years 2007 and 2008. Carbon intensity and trade intensity are computed for each sector as documented in Section 2.

Permit allocations in the reference scenarios are calculated as follows. The grandfathering allocation corresponds to the average CO_2 emissions, as calculated above. The benchmarking allocation is the mean allocation from 2013 until 2020, taken from the official NIMs for the six countries. The overall cap $\bar{Q}$ is calculated as the sum of the reference allocations across all firms in the sample.

C.4 Dynamic programming using `cake.ado`

The ado file cake.ado uses dynamic programming to solve a minimization program of the type

$$\min_{x_i} \sum_{i=1}^{N} f_i(x_i) \qquad \text{s.t.} \sum_{i=1}^{N} x_i \leq \bar{x}.$$

Before calling cake.ado we need to

1. Discretize the vector x on a finite support. For simplicitly, suppose that we have discrete support $1, 2, \ldots, \bar{x}-1, \bar{x}$.

2. Evaluate, for each firm i, the risk at each point of the support:

$$\mathbf{f} = \begin{bmatrix} f_i(0) \\ f_i(1) \\ \vdots \\ f_i(\bar{x}-1) \\ f_i(\bar{x}) \end{bmatrix}$$

The vector $\mathbf{f}$ is an input to the STATA program cake.ado. The program does the following:

1. Set the continuation value for the last firm to $v_N(x) = f_N(x)$ and iterate backwards. The continuation value for the penultimate firm is given by $v_{N-1}(x) = \min_c \ f_{N-1}(c) + v_N(x-c)$. To do this numerically, v_{N-1}must be evaluated for each x and c. This is done by building a matrix with values $v_{N-1}(x,c) = f_{N-1}(c) + v_N(x-c)$ where x shifts along the rows and c along the columns. The components of this matrix are:

$$V_N(x) = \begin{bmatrix} v_N(0) & B & B & B \\ v_N(1) & v_N(0) & B & B \\ \vdots & \vdots & \ddots & B \\ v_N(\bar{x}) & v_N(\bar{x}-1) & \ldots & v_N(0) \end{bmatrix}$$

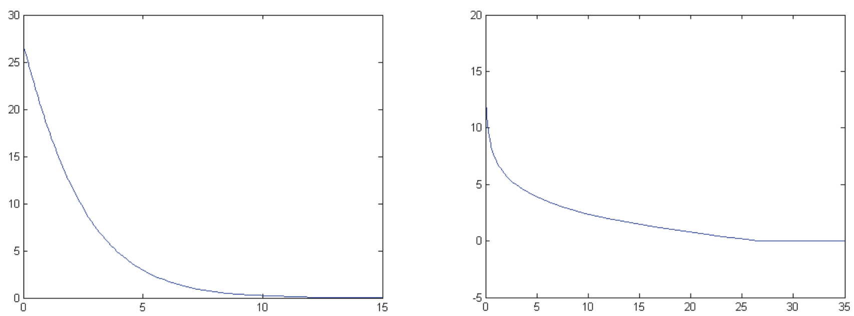
   and

$$F_{N-1}(c) = \begin{bmatrix} f_{N-1}(0) & B & B & B \\ f_{N-1}(0) & f_{N-1}(1) & B & B \\ \ddots & \vdots & \ddots & B \\ f_{N-1}(0) & f_{N-1}(1) & \ldots & f_{N-1}(\bar{x}) \end{bmatrix}$$

   where B is a large number. The vector $v_{N-1}(x)$ is obtained by adding the two matrices and picking the minimum in each row. The policy function $a_{N-1}(x)$ is obtained in a similar fashion, as the $\arg\min$of each row of the matrix.

Figure C.2: Function plots: damage=100, $\beta_0 = 1$, $\beta_1 = .5$,

(a) Risk function (b) Inverse risk function (allocation)



2. This step is repeated recursively for all firms. The result is a vector $v_1(x)$ which gives the minimal risk for every possible initial allocation of permits, and a policy matrix A which results from concatenating all the a vectors.

3. To obtain the optimal allocation, one can start with allocation $\bar{x}$ and consult the policy function for the first firm (in the first column of A). For example, if $a_1(\bar{x}) = k \leq \bar{x}$ we know that the row minimum was in column k which means that the first firm should receive $k-1$ free permits. Then move on to the second column of A and evaluate at $x = \bar{x} - k$ to get the allocation for firm 2, and so on.

Figure C.2 shows the shape of the risk function (in panel a) and of the inverse risk function (in panel b). Since negative allocations are not possible, we need to truncate the function at the root and assign 0 permits to all risk allocations larger than the root. Moreover, firms that do not respond to free permit allocation at all ($\beta_1 = 0$) are allocated 0 permits in a separate step prior to optimization.

D Output-based updating

In Section 4 the firm's response to free permits is modeled in terms of the *probability* of exit from the EU for different allocation levels. In line with the institutional framework of capacity-based updating, there is no intensive margin-response on employment or output. This section shows that a similar reduced-form response of home (EU) employment (or output) can be obtained when allowing for output adjustments in a more flexible framework.

Suppose that a firm's final output Q is produced by means of a Leontief production function

$$Q = \min_{\nu \in [\varepsilon, 1]} \{v_\nu\}$$

using a continuum of intermediate input varieties v_ν. Production of a variety can be in home or foreign. Varieties are produced with labor and energy leading to CO_2 emissions. Home has lower effective wages (e.g. because of higher productivity), foreign has lower energy costs.

Varieties differ in the amount of energy required to produce them. The technology for producing varieties is Leontief

$$v_\nu = \min \left\{ L_\nu, \frac{1}{\gamma \nu} E_\nu \right\}$$

where E_ν is the amount of energy and L_ν labour. Energy intensity of production is highest for variety $\nu = 1$ and lowest for variety $\nu = \varepsilon$. The parameter γ scales the overall energy intensity of a firm. The cost of producing one unit of a variety ν is given by

$$c_\nu = W_L + \gamma \nu W_E$$

For simplicity we normalize the energy cost in foreign and the wage cost in home to 0. If the wage in foreign is equal to w and the energy cost in home is equal to τ we can find the marginal variety s by equalizing the costs in home and foreign:

$$\tau \gamma s = w \tag{D.1}$$

The optimal offshoring decision

$$s = \begin{cases} \varepsilon & \text{if } \frac{w}{\gamma \tau} < \varepsilon \\ \frac{w}{\gamma \tau} & \text{if } \varepsilon \leq \frac{w}{\gamma \tau} < 1 \\ 1 & \text{if } \frac{w}{\gamma \tau} \geq 1 \end{cases}$$

implies that higher energy costs at home lead to a larger number of varieties being produced abroad. Moreover, firms whose energy intensity increases faster across varieties (high γ) produce a larger share of intermediates abroad.

The unit and marginal costs of producing a unit of final output will be equal to

$$c(s) = \int_{\varepsilon}^{s} \tau \gamma \nu d\nu + \int_{s}^{1} w d\nu = \frac{1}{2} \tau \gamma \left(s^2 - \varepsilon^2\right) + w(1 - s)$$

Since $\frac{\partial c(s)}{\partial s} = \tau\gamma s - w$, the heuristic derivation of the marginal variety in (D.1) gives rise to the same interior solution as the unit cost minimization program.

Free allocation Free allocation in Phase III of the EU ETS consists of a lump sum allocation $\bar{A}$ which is based on historical output and sector specific benchmarks for the emissions intensity of output. When a firm outsources a substantive share of production by shifting the production of certain varieties to foreign, the allocation is adjusted downwards. As discussed above, this practice likens free permit allocation to a step function in output. In the main text, we considered a simplified version of this step function which had only a single step (all or nothing). Here we consider the opposite extreme and assume that the number of permits that the firm can retain, A_i, is directly proportional to output if output is smaller than historical domestic output $H = \bar{s}\bar{Q}$

$$A = \begin{cases} \frac{sQ}{H}\bar{A} & \text{if } \frac{sQ}{H} < 1 \\ \bar{A} & \text{otherwise} \end{cases} \tag{D.2}$$

Profit maximization To complete the description of the firm's problem we have to make an assumption about demand. Suppose we have monopolistic competition with linear demand

$$P = a - bQ$$

Profits are given by

$$\Pi\left(Q, s, \bar{A}\right) = aQ - Q^2 b - Qc\left(s\right) + \frac{sQ}{H}\bar{A}$$

and the profit maximization problem becomes

$$\max_{Q,s} \Pi\left(Q, s, \bar{A}\right)$$

The first order conditions are given by

$$[Q] \qquad a - 2Qb - c\left(s\right) + \frac{s\bar{A}}{H} \geq 0 \qquad \wedge \tag{D.3}$$

$$[s] \qquad \frac{Q\bar{A}}{H} - Q\left(\tau\gamma s - w\right) \geq 0 \tag{D.4}$$

For an interior solution condition (D.3) implies

$$Q(s) = \frac{a - c(s) + \frac{s\bar{A}}{H}}{2b}$$

From (D.4) we can solve for the optimal relocation threshold s^*:

$$s^* = \begin{cases} \varepsilon & \text{if } \frac{1}{\gamma\tau}\left(w + \frac{\bar{A}}{H}\right) < \varepsilon \\ \frac{1}{\gamma\tau}\left(w + \frac{\bar{A}}{H}\right) & \text{if } \varepsilon \leq \frac{1}{\gamma\tau}\left(w + \frac{\bar{A}}{H}\right) < 1 \\ 1 & \text{otherwise} \end{cases} \tag{D.5}$$

From (D.3) and (D.5) it is straightforward to calculate total output Q^*, domestic output s^*Q^* and domestic employment

$$L^* = \begin{cases} (s^* - \varepsilon)\,Q^* & \text{if } (s^* - \varepsilon)\,Q^* < H \\ H & \text{otherwise} \end{cases} \tag{D.6}$$

where the two cases follow from the allocation rule in equation (D.2).

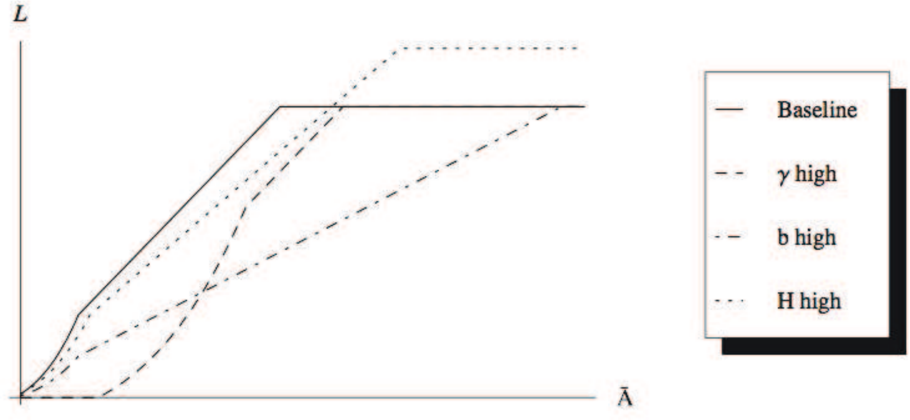
Figure D.1 plots employment in home as a function of freely allocated permits $\bar{A}$ for different parameter values. In the baseline case, employment initially increases with $\bar{A}$. The increase is more than proportional when $s < 1$, as the firm responds to free permits both by increasing the share of varieties produced at home and by increasing final output Q. Once all varieties have been repatriated, further increases in $\bar{A}$ linearly increase home employment until the firm reaches its historical output level.

Upon comparing the different cases shown in Figure D.1, we see that the response to free permits is slower when the firm is more energy intensive (γ high) because a stronger incentive is required to repatriate the more energy intensive varieties. The employment response is also slower whenthe demand elasticity is lower than in the baseline case (b high). This is because the firm has more market power and chooses lower levels of output irrespective of the share of intermediates produced at home. [5] Finally, firms with a higher historical output (H high) continue to increase employment at higher levels of $\bar{A}$ than in the baseline case. The initial marginal impact in this case is smaller than in the baseline case because the actual amount of permits received, A, is inversely proportional to the (larger) reference output.

In sum, this appendix has illustrated that the S-shaped function we have used in the main text to approximate the response of output and employment to free permit allocation provides a reasonable approximation even under the (counterfactual)

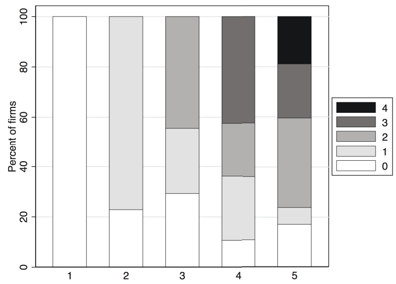
[5] Hence the marginal impact of repatriating a variety and in turn the marginal impact of additional free allocations is lower.

Figure D.1: Home employment as function of free permits



assumption that free permit allocation is directly proportional to output.

Figure E.1: Impact of free allocation on the vulnerability score



Notes: The chart shows the conditional distribution of the reduction in the vulnerability score when firms receive free permits for 80% of their direct carbon emissions. The conditioning variable is the vulnerability score in the absence of free permits. For example, the fifth bar represents firms that responded that future carbon pricing would likely force them to close down or relocate. One fifth of these firms reported that receiving free permits would have no impact on this decision whereas another fifth reported that this would neutralize any negative impact on domestic production.

E Additional Tables and Figures

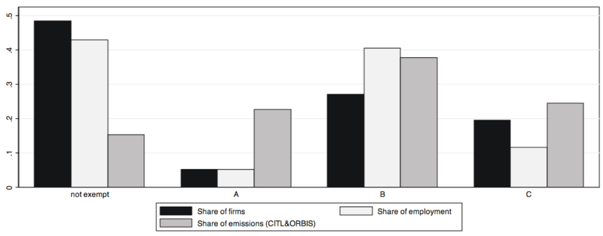
Table E.1: Sector classification

Sector	NACE Sectors	CITL 2008 sectors
Food & Tobacco	15, 16	
Textile & Leather	17, 18, 19	
Wood & Paper	20,21	9
Publishing	22	
Fuels	23	2,3
Chemical & Plastic	24, 25	
Glass	261	7
Ceramics	262	8
Cement	264, 265,266	6
Other Minerals	267, 268	
Iron & Steel	271, 272, 273, 275	5
Other Basic Metals	274	
Fabricated Metals	28	
Machinery & Optics	29, 30, 31,33	
TV & Communication	32	
Vehicles	34,35	
Furniture & NEC	36	

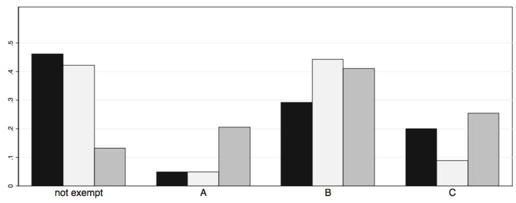
Notes: NACE sectors codes are based on NACE 1.1. NEC: Not elsewhere classified.

Figure E.2: Relative size of exemption groups in different samples

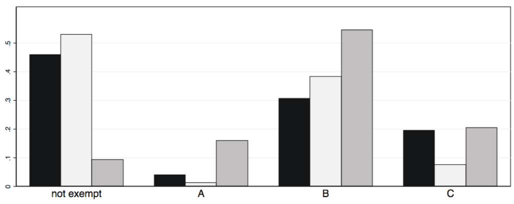
(a) All matched EU ETS firms

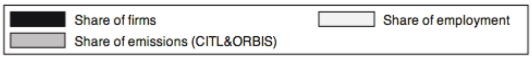


(b) Matched EU ETS firms in 6 interview countries



(c) Interviewed EU ETS firms only

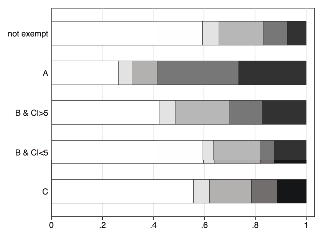




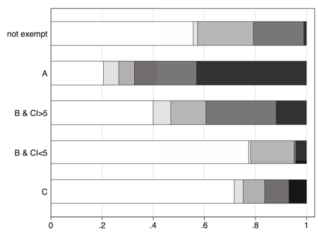
Notes: The charts display the relative size of each category of sectors in the EU ETS defined by the exemption criteria. The first bar indicates the category's share of firms, the second bar its share in employment, and the third bar its share in CO_2 emissions, based on figures from the CITL-ORBIS match. The sample underlying figure (a) includes all manufacturing firms in the EU ETS which we could match to ORBIS. Figure (b) is based on all such firms located in the six countries under study. Figure (c) is based only on EU ETS firms that we interviewed.

Figure E.3: Distribution of the vulnerability score

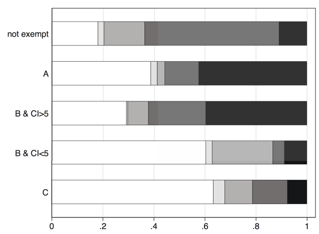
(a) Shares in number of firms



(b) Shares in employment



(c) Shares in CO_2 emissions



Notes: The graphs show the distribution of the vulnerability score for interviewed firms included in the EU ETS and part of each group of sectors defined in Section 2.2. Panel a reports the shares of firms, panel b employment shares, and panel c CO_2 emission shares, based on average permits surrendered in 2007 and 2008.

F Appendix References

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G Questionnaire

Questionnaire

Questions	Values	Coding description
I. Introduction		
1. A bit about your business		
(a) Is your firm a multinational? If yes, where is the headquarters?	no, list of countries, dk, rf	"No", if not a multinational; country where headquarters is located if a multinational
(b) On how many production sites do you operate (globally)?	number, dk, rf	Number of sites globally (approximate if unsure)
(c) How many of these sites are situated in the EU?	number, dk, rf	Number of sites in the EU
(d) How many of these sites are situated in the UK/B/FR/...?	number, dk, rf	Number of sites in current country
2. A bit about you		
(a) Job title	text	
(b) Tenure in company	number, rf	
(c) Tenure in current post	number, rf	
(d) Managerial background	commercial, technical, law, other	
3. EU ETS involvement		
As you might know, the European Union Emissions Trading System (referred to as EU ETS, hereafter) is at the heart of European climate change policy. (a) Is your company (or parts thereof) regulated under the EU ETS? (b) Since when?	no, list of years 2005-2009, yes dk year, dk, rf	
(c) How many of your European business sites are covered by the EU ETS?	number, dk, rf	
4. Site location		
For single plant firms and interviewees based at a production site: Could you tell me the postcode of the business site where you	text	Records the postcode

Questions	Values	Coding description	
are based? *For multi-plant firms where the interviewee is located at a non-production site:* Some of the questions I am going to ask you next are specific to a production site within your firm. Please choose a particular production site and answer my questions for the particular site throughout the interview. The site should be the one you know best, the largest one, or the one nearest to you. If you are in the EU ETS, please pick a site covered by the EU ETS. Could you tell me the postcode of the chosen site?			
II. Impact of EU ETS			
5. EU ETS stringency (If not an EU ETS firm, continue with question 9)			
(a) How tough is the emissions cap/quota currently imposed by the EU ETS on your production site? (b) Can you describe some of the measures you put in place to comply with the cap?	1-5, dk, rf, na	Low	Cap is at business as usual.
		Mid	Some adjustments seem to have taken place, however nothing which led to fundamental changes in practices; e.g. insulation, etc.
		High	Measures which led to fundamental changes in production processes; e.g. fuel switching; replacement of essential plant and machinery.
(c) What is the annual cost burden of being part of the EU ETS? For example, monitoring, verification and transaction costs; the cost of buying permits or reducing emissions. *If the manager does not understand the question:* Imagine your installation was not part of the EU ETS this year, what cost saving would your firm do?	number	Absolute number	
	percentage	Or percentage of annual operating cost	
6. EU ETS management			
Ask only multi-plant firms: Is EU ETS compliance managed on the production site or elsewhere?	site, other site, national firm, european firm, dk, rf, na		

Questions	Values	Coding description	
7. ETS trading			
(a) In **March** of this year (i.e. **before** the compliance process), what was your allowance position on this site? (b) Were you short or long in allowances?	long, short, balanced, dk, rf, na		
	text	If the manager happens to mention the detailed number of allowances, make a note of it in this field.	
(c) Before the compliance process in April, did you buy or sell allowances on the market or over the counter from other firms? (d) If not, why not?	buy, sell, both, no: only trading during compliance period, no: no need, no: image concerns, no: transaction costs, no: other, dk, rf, na		
(e) If yes, how frequently?	daily, weekly, monthly, quarterly, bi-annual, yearly, dk, rf, na		
(f) **In April this year**, what was your position after the compliance process?			
If answers "long": Did you bank permits for future years? Why?	banking to emit more in following years, banking to sell at a higher ETS permit price in future, banking dk why, long for pooling, dk, rf, na	Banking reason.	
If answers "balanced/compliant" or "short": Did you borrow permits from next year's allowance? Why?	borrowing to emit less in following years, borrowing to buy at a lower ETS permit price in future, borrowing to be compliant, borrowing dk why, rf, dk, na	Borrowing reason. *Note: Only choose "borrowing to be compliant" if the manager is very short sighted and doesn't seem to understand he will eventually have to either emit less or buy permits*	
If answers "short": Why did you remain short?	short for pooling, short and paid fine, other, rf, dk, na	Short reason.	
	text	If "other": why?	
(g) Has this site exchanged emission permits with other installations belonging to your company that are part of the EU ETS? (pooling)	yes, no, rf, dk, na		
8. Rationality of market behaviour			
(a) How do you decide how many permits to buy or sell or trade at all? (b) Did you base this decision on any forecast about prices and/or energy usage?	1-5, dk, rf, na	Low	Take their permit allocation as a target to be met as such and do not take into account the price of permits or the cost of abatement. Just sell if there is a surplus or buy if there is a deficit.
		Mid	Are in the process of learning how the market works and in the first

Questions	Values	Coding description	
(c) Did you trade permit revenue off against emission reduction costs in your planning on this issue?			years did not have any market driven attitude, but now have someone in charge of managing the ETS so as to minimize compliance cost. This person has experience in financial markets and sometimes interacts with the production manager.
		High	Company has a thorough understanding of the site-specific CO2 abatement cost curve. Trading is used as a tool to reduce compliance cost and to generate extra revenues from excess abatement. Moreover, company forms expectations about permit price and re-optimizes abatement choice if necessary. Trader resorts to futures and derivatives to manage ETS permits as a financial asset.
9. Anticipation of phase III			
(a) Do you expect to be part of the EU ETS from 2012 onwards? *If not, continue with question 10*	yes, no, dk, rf, na		
(b) How stringent do you expect the next phase of the EU ETS (from 2012 to 2020) to be? (c) Will it be tough for your firm to reach such a target? Can you describe some of the measures you would have to put in place? (d) Do you believe the allowances will be distributed through an auctioning mechanism? (e) Is it likely that sanctions for non-compliance will become more stringent?	1-5, dk, rf, na	Low	Cap for phase III is anticipated to be comparable to business as usual. The manager believes there will be no additional sanctions and that they will receive the permits for free.
		Mid	Phase III is likely to trigger some adjustments, however nothing that will lead to fundamental changes in practices. Only a small part of permits will be auctioned and sanctions are not expected to be very high.
		High	The presence of strong sanctions, extensive use of auctioning and more stringent targets in Phase III is anticipated. It is likely to imply the adoption of measures which will lead to fundamental changes in production processes. It might also imply the closure of the plant, or redundancy of more than 20% of employment.
(f) Do you expect to transfer unused (banked) ERUs or CERs from Phase II to Phase III ? *Note: ERUs are Emission Reduction Units stemming from Joint Implementation projects. CERs are Certified Emission Reductions stemming from Clean Development Mechanism projects.*	EUAs, ERUs, CERs, EUAs and ERUs, EUAs and CERs, ERUs and CERs, all three, no, dk, rf, na		

Questions	Values	Coding description
10. Awareness		
(a) Are climate change topics discussed within your business? Can you give examples? (b) Are climate change related issues formally discussed in management meetings? Can you give examples? (c) Do your strategic objectives mention climate change? (d) Did you commission reports or studies on how climate change will affect your business?	1-5, dk, rf, na	*Note: Give minimum score of 3 to ETS firms and probe directly for 4 or 5, skipping (a) and (b).* Low: Don't know if threat or opportunity. No awareness. Mid: Some awareness backed up by evidence that this is being formally discussed by management. High: Evidence that climate change is an important part of the business strategy.
Mentioned positive impact:	yes, no	
III. Prices		
11a Energy price expectations		
By how many percent do you expect energy prices to go up or down by 2020?	percentage, dk, rf	Expected price change in percent of today's price. *Note: This price includes the effect of current and future climate change policies on the energy price.*
	percentage, dk, rf	Upper bound on expected price change – record only if interviewee mentions it.
	percentage, dk, rf	Lower bound on expected price change – record only if interviewee mentions it.
11b Carbon price expectations		
(a) As you might know, the EU has committed to reducing greenhouse gas emissions by 20%-30% over the next decade. What price do you expect to pay for emitting one tonne of CO2 in 2020?	percentage, dk, rf percentage, dk, rf yes, no, rf, dk	Expected price in Euros per ton of CO2. Or expected price change in percent of today's price. Knows today's price of CO2.
(b) What price do you expect in the worst-case scenario?		Upper bound in Euros per ton of CO2.
(c) What price do you expect in the best-case scenario?		Lower bound in Euros per ton of CO2.
12. Future impact of carbon pricing		
(a) Do you expect that government efforts to put a price on carbon emissions will force you to outsource parts of the	1-5, dk, rf	Low: No impact of this kind. Mid: Significant reduction (>10%) in production/employment due to outsourcing.

Questions	Values	Coding description
production of this business site in the foreseeable future, or to close down completely?		High: Complete close-down.
(b) What carbon price do you associate with this scenario? (Assume that you would have to pay for all allowances.) *Note: The price relates to the scenario given under (a). If answered "no impact" under (a), skip this question.*	number, dk, rf, na	Euros per ton
(c) How would your answer to the previous questions change, if you received a free allowance for 80% of your current emissions? *Note: If answered "no impact" under (a), skip this question.*	1-5, dk, rf, na	Low: No impact of this kind. Mid: Significant reduction (>10%) in production/employment due to outsourcing. High: Complete close-down.
(d) *Note: Only ask if answered "no impact" under (a).* At what carbon price level would you be forced to close your plant down? ***If the manager has no idea or says it would need to be very high, try different prices, starting high, f****or example:* If you had to pay 200 Euros/ton of carbon, would you need to close down?	number, dk, na	**Euros per ton**
(e) How did you reach this conclusion? (f) How concrete are the plans for outsourcing or closure?	1-5, dk, rf, na	Low: Gut feeling of the manager. Mid: Response is based on a plausible argument. For example, interviewee discusses available technological options and associated cost and relates them to profit margins. High: Commissioned a detailed study of abatement options and associated cost (in-house or external).
(g) What fraction of an energy price or carbon price increase can you pass on to your customers?	percentage, dk, rf	
IV. Competition and customers		
13. Competitors		
(a) Can you tell me the number of firms in the world which compete with you in one or more local markets? *Note: For multi-product multi-plant firms refer to the market for the products created on the current site referred to during*	number, dk, rf	

Questions	Values		Coding description
this interview. For instance, for multi-plant firms start the question with "For the products produced at the production site, can you tell me ..."			
(b) How many of them are located within the EU?	number, dk, rf		
(c) How many of them are located in your country?	number, dk, rf		
(d) Location of main competitor (country)	list of countries, dk, rf, na		
(e) Do you know in which country your main competitor does most of its production?	same, EU, non-EU, list of countries, dk, rf, na		
14. Location of Customers			
(a) Share of sales exported (to the EU and the rest of the world)	percentage, dk, rf		
(b) Share of sales exported to EU countries	percentage, dk, rf		
(c) Are your products sold mainly to consumers or to other businesses?	B2B, final customer, dk, rf		
15. Customer pressure			
(a) Are your customers concerned about your GHG emissions? (b) How do they voice this concern? (c) Do your customers require hard data on your carbon emissions?	1-5, dk, rf	Low	"B2C" - Not aware that emissions performance is of significant concern to consumers of their product. "B2B" - Not aware that businesses they supply to are concerned about the emissions of the plant; quality and price are the only considerations.
		Mid	"B2C" - The business is aware of the importance of climate-change issues in general and so are conscious that their customers may consider GHG performance to be important, although they do not expect or require data as proof. "B2B" - Customers set ISO 14001 as a precondition to suppliers. Evidence of environmental compliance is requested, but details of emissions figures are not required.
		High	"B2C" - Being seen to reduce GHG emissions is thought to be important in the purchasing decisions of the firm's consumers. This has been determined by market research or consumers have voiced their concern through other means. Customers also ask for certified data on emissions during production or usage. A customer-friendly system to recognize the best products in terms of energy efficiency is often available in the market (e.g. EU energy efficiency grade for home appliances). "B2B" - Customers ask for evidence of external validation of GHG figures. Customers request information on carbon emissions as part of their own supply chain carbon auditing. Customers conform to PAS 2050 or other national standard in carbon foot-printing and so require detailed information on a regular basis.
16 Climate change related products			
16.1 Existing climate change related products			
(a) Do you currently produce climate change related products at your production site? (Products that help your customers to reduce GHG emissions or adapt to climate change) (b) Can you give examples? (c) How important are these products as a source of revenue within your plant?	1-5, dk, rf	Low	No climate change related products and no plans to introduce any.
		Mid	Some climate change related products. These products are however not the main profit or revenue source of the firm.
		High	The majority of the firm's output can be considered a climate change related product.
16.2 Climate change related product innovation			
(a) Globally, is your company currently trying to develop new products that help your customers to reduce GHG emissions? (b) Can you give examples? (c) What fraction of your Research & Development funds are used for that? (Less than 10%, more than 10%?)	1-5, dk, rf	Low	No efforts to develop climate change related products.
		Mid	Some efforts but it is not the main objective of the firms R&D efforts.
		High	The firm is focusing all product R&D efforts on climate change.

Questions	Values	Coding description	
V. Measures			
17. Energy monitoring			
(a) How detailed is your monitoring of energy usage? (b) How often do you monitor your energy usage? Since when? (c) Describe the system you have in place.	1-5, dk, rf	Low	No monitoring apart from looking at the energy bill.
		Mid	Evidence of energy monitoring as opposed to looking at the energy bill, i.e. there is some consciousness about the amount of energy being used as a business objective. However, discussions are irregular and not part of a structured process and are more frequent with price rises. Not more than quarterly monitoring of energy.
		High	Energy use is measured and monitored constantly and is on the agenda in regular production meetings. Energy use in the plant is divided up in space (by production line, machine or similar) and monitored over time (daily, hourly or continuously). The amount of energy rather than the cost is focused on.
	2000 and earlier, list of years 2001-2010, dk, rf, na	Start date (put "na" if score is "1")	
18. Targets on energy consumption for management			
(a) Do you have any targets on energy consumption which management has to observe? (e.g. kWh of electricity)	no targets, relative quantity targets, absolute quantity targets, absolute and relative quantity targets, only expenditure targets, dk, rf	Type	
(b) Can you describe some of the challenges you face in meeting the targets? (c) How often do you meet these targets? Do you think they are tough? *Note: If the manager replies they have EU ETS/CCA targets, ask "have these been translated into internal targets for management?"*	1-5, dk, rf	Low	No targets.
		Mid	Targets exist but seem easy to achieve.
		High	Evidence that targets are hard to achieve. Detailed.
(d) By approximately how much does this require reducing your current energy consumption in the next 5 years (10%, 25%, 50%)?	percentage, dk, rf, na		
	number, dk, rf, na	Horizon (number of years)	

Questions	Values	Coding description	
Note the timetable for the target (e.g. 5 years or other number given by interviewee).			
(e) Since when do you have these targets?	2000 and earlier, list of years 2001-2010, dk, rf, na		
19. GHG monitoring			
(a) Do you explicitly monitor your GHG emissions? Since when? (b) How do you estimate your GHG emissions? (c) Are your GHG estimates externally validated?	1-5, dk, rf	Low	No specific GHG monitoring.
		Mid	Detailed energy monitoring with clear evidence for carbon accounting (at least firm level). Manager is aware that energy figures need to be scaled by carbon intensity.
		High	Carbon accounting of both direct and indirect emissions (supply chain emissions). External validation of GHG figures.
	2000 and earlier, list of years 2001-2010, dk, rf, na	Start date (put "na" if score is "1")	
20. Targets on GHG emissions for management			
(a) Do you have any targets on GHG emissions which management has to observe?	no targets, direct emissions, indirect and direct, dk, rf		
(b) Can you describe some of the challenges you face in meeting the targets? (c) How often do you meet these targets? Do you think they are tough? *Note: If the manager replies they have EU ETS/CCA targets, ask: H*ave these been translated into internal targets for management?	1-5, dk, rf	Low	No targets for GHG emissions.
		Mid	There is some awareness of the contribution of different energy sources and production processes to emissions, but this is a secondary consideration to cost focused energy targets. There is some degree of difficulty in the targets.
		HIgh	There are separate targets for GHGs, distinct from energy use. GHG emissions are a KPI (Key Performance Indicator) for the firm. The contribution of each energy source and the production process to GHG emissions is known and suggested improvement projects for the production are assessed on their potential impact on carbon as well as energy efficiency.
(d) By approximately how much do these targets require you to reduce your emissions in the next 5 years (10%, 25%, 50%) compared their current level?	percentage, dk, rf, na		
	number, dk, rf, na	Horizon (number of years)	

Questions	Values	Coding description	
Note the timetable for the target (e.g. 5 years or other number given by interviewee)			
(e) When did you start having targets on GHG emissions?	2000 and earlier, list of years 2001-2010, dk, rf, na		

21. Target enforcement

(a) What happens if energy consumption or GHG emission targets are not met? (b) Do you publicize targets and target achievement within the firm or to the public? Can you give examples? (c) Are there financial consequences in case of non-achievement? (d) Is there a bonus for target achievement?	1-5,dk,rf	Low	No targets or missing targets do not trigger any response.
		Mid	Both target achievement and non-achievement are internally and externally communicated.
		High	Target non-achievement leads to financial consequences internally and/or externally; including penalties, e.g. staff does not get bonus.

22. Emission-reducing measures

(a) Can you tell me what measures you have adopted in order to reduce GHG emissions (or energy consumption) on this site? DO NOT PROMPT with the list if doesn't have an idea, rather ask: Have you bought any new equipment, or have you changed the way you produce?	List of tickboxes	I. Heating and cooling: 1- Optimised use of process heat 2- Modernisation of cooling/refrigeration system 3- Optimisation of air conditioning system 4- Optimisation of exhaust air system and/or district heating system
		II. More climate-friendly energy generation on site: 1- Installation of combined heat and power (CHP) plant / cogeneration 2- Biogas feed-in in local combined heat and power plant or domestic gas grid 3- Switching to natural gas 4- Exploitation of renewable energy source
		III. Machinery: 1- Modernisation of compressed air system 2- Other industry-specific production process optimisation/machine upgrade 3- Production process innovation
		IV. Energy management: 1- Introduction of energy management system 2- Submetering / upgrade of an existing energy management system

Questions	Values	Coding description
		3- (External) Energy audit 4- Installation of timers attached to machinery 5- Installation of (de-)centralised heating systems
		V. Other measures on production site: 1- Modernisation of lighting system 2- Energy-efficient site extension/improved insulation/introduction of building management 3- Employee awareness campaigns and staff trainings 4- Non-technical reorganisation of production process 5- Installation of energy-efficient IT-system 6- Improved waste management/recycling
		VI. Beyond production on site: 1- Introduction of climate-friendly commuting scheme 2- Consideration of climate-related aspects in investment and purchase decisions 3- Consideration of climate-related aspects in distribution 4- Customer education programme 5- Participation in carbon offsetting schemes
(b) Which one of these measures achieved the largest carbon saving?	measure code	*Fill in the code corresponding to the measure in (a) (e.g. II-4 for "Exploitation of renewable energy source").*
(c) By how much did this measure reduce your total energy consumption?	percentage, dk, rf, na	
(d) By how much did this measure reduce your total GHG emissions?	percentage, dk, rf, na	
(e) What motivated the adoption of these measures?	EU ETS, energy cost saving / high profitability, pollution reduction, reputation, customer pressure, employee initiative, public investment support, compliance with regulation, compliance with expected future regulation, other, dk, rf, na	Main motivation (select only ONE)
	text	Other motivation (if not in tick boxes, or second)

Questions	Values	Coding description	
(f) How did you learn about this measure?	consultant, government, customer, supplier, employee, R&D project, competitor, other, dk, rf, na	Tick more than one option, if different sources mentioned	
(g) When did you implement this measure?	2000 and earlier, list of years 2001-2010, dk, rf, na		

VI. Innovation, barriers to investment and management

23. Climate change related process innovation			
(a) Do you dedicate staff time and/or financial resources to finding new ways of reducing the GHG emissions at your facility? Did you commission any studies for that purpose? (b) Can you give examples? (c) What fraction of your firm's global Research & Development funds are used for that? (less than 10%, more than 10%?) *Note: This does not include expenses for staff trainings or energy monitoring, but actual innovation.*	1-5, dk, rf	Low	No R&D resources committed to reducing GHG emissions.
		Mid	Evidence of R&D projects to reduce emissions.
		High	Evidence that this kind of R&D is an important component in the company's R&D portfolio (5 or higher).
24. Barriers to adopting energy-efficiency investments			
(a) Can you give one example of a measure to enhance energy efficiency which was considered, but eventually not adopted?	List of tickboxes	Same list as for question 22a.	
(b) Which payback time was required in the economic evaluation of this measure?	number, dk, rf, na	"Years"; if in months, put equivalent in years, e.g. record 6 months as 0.5.	
(c) Is this payback time longer or shorter than the one applied to non-energy related measures to cut costs?	1-5, dk, rf, na	Low	Longer, i.e. much less stringent
		Mid	Equal
		High	Shorter, i.e. much more stringent
(d) If different: why?	text		
(e) Was uncertainty about future prices or regulation important for the decision to reject?	no, yes_prices, yes_regulation, yes_both, dk, rf, na		

Questions	Values	Coding description
(f) What other factors were influential in the decision?	text	
(g) Has the current economic downturn affected your investment criteria for clean technologies? How?	no, favors clean, favours other, more stringent overall, less stringent overall, dk, rf, na	
25. Further reductions		
(a) By how much (in percentage points) could you - at current energy prices - further reduce your current GHG emissions without compromising your economic performance? (i.e. how much more emission reduction could be achieved without increasing costs)	percentage, dk, rf	
(b) If so, why have you not implemented these measures yet?	text	
(c) What further GHG emission reduction (in percentage points) would be technologically possible (although not necessarily at no extra cost)?	percentage, dk, rf	Notes: Assuming that production stays constant and that no processes are being outsourced. This should not include emission reduction achieved by switching to renewable electricity. Include emissions reductions through combined heat and power however.
26. Manager responsible for Climate Change issues		
(a) At the management level, who is responsible for dealing with climate change policies and energy and pollution reduction in the firm nationally? What is the official job title? *Note: If several, ask for highest-ranking. If nobody, put title "no clear responsibility".*	text	Job title of the manager
(b) How far in the management hierarchy is this manager below the CEO? (figure out through sequential questioning if necessary)	CEO, number, no clear responsibility, dk, rf	No of people between CEO and Manager, e.g. if reports directly to CEO, put 0
(c) Has there recently been a change in responsibilities for climate change issues? When?	no change, list of years 2000-2010, yes dk year, dk, rf	
(d) How far in the management hierarchy was this manager below the CEO? (figure out through sequential questioning if necessary)	CEO, number, no clear responsibility, dk, rf	
	text	Record past manager title if mentioned, but do not prompt for it.

Questions	Values	Coding description
VI. Firm Characteristics		
27. Firm/Plant Details		
(a) How many people are employed in the firm globally (including this country)? *Note: If a multinational, ask for the whole group's number.*	number, dk, rf	
(b) How many people does the firm employ in your country?	number, dk, rf	
(c) How many people are employed at the current site?	number, dk, rf	
(d) Annual Energy Bill-Annual:	number, dk, rf	
		Do not ask, but in case interviewee does not know the absolute number and answers with one of the following:
	percentage, dk, rf, na	Energy cost as percentage of ***turnover***
	percentage, dk, rf, na	Energy cost as percentage of ***costs***
(e) Total annual running costs (wage cost + materials, including energy):	number, dk, rf	
Answered (d) and (e) at the site level or at the company level?	site, company, na	
(f) Does your company purchase renewable power?	yes, no, dk, rf	*Note: Do not include electricity generated on site.*
(g) Does this site do any product R & D? *Note: Do not dwell on this question, make a judgement from first answer.*	yes, no, dk, rf	
(h) Is Marketing for your products done from this site? *Note: Do not dwell on this question, make a judgement from first answer.*	yes, no, dk, rf	
(i) Does this site have an environmental management system (ISO 14000)?	yes, no, dk, rf	

Questions	Values	Coding description
VII. Country-specific policies		
UNITED KINGDOM		
UK.1 Participation in voluntary government climate change policies		
(a) Are you aware of voluntary government schemes to help businesses reduce GHG pollution? (b) Which ones? (c) Are you participating in any?	no, list of years 2001-2009, dk, rf, na	Carbon Trust Online Tools (Benchmarking Tools, Action Plan Tool) When?
		Carbon Trust Energy Audit or Advice? (CTaudit)
	no, list of years 2001-2009, dk, rf, na	Innovation grants from the Carbon Trust? When?
		Carbon Trust Standard
	no, list of years 2001-2009, dk, rf, na	Enhanced Capital Allowance scheme? (ECA)
	no, list of years 2001-2009, dk, rf, na	
	no, list of years 2001-2009, dk, rf, na	
UK.2 Participation in Climate Change agreement		
(a) Is your company (or parts thereof) subject to a UK Climate Change Agreement? (b) Since when?	no, list of years 2001-2009, dk, rf, na	
(c) How stringent is the target imposed by the CCA? (d) Can you describe some of the measures you had to put in place to comply with the cap?	1-5, dk, rf, na	Low: No targets. Mid: Targets exist but seem easy to achieve. High: Evidence that targets are hard to achieve. Detailed description of serious problems in achieving targets.
((e) Did you buy or sell emission rights via the UK ETS?	no because of image concerns, no because no capacity, no other, bought, sold, both, dk, rf, na	
BELGIUM		
B.1 Participation in industry agreements (accords de Branche/Bechmarkconvenanten) (a) Is your company (or parts thereof) subject to an industry agreement?	no, list of years 2001-2009, dk, rf, na	

Questions	Values	Coding description
(b) Since when?		
(c) How stringent is the target imposed by the agreement? (d) Can you describe some of the measures you had to put in place to comply with the cap?	1-5, dk, rf, na	Low: No targets. Mid: Targets exist but seem easy to achieve. High: Evidence that targets are hard to achieve. Detailed description of serious problems in achieving targets.
B.2 Do you benefit from any tax reduction from the Federal government because of investments that reduce energy consumption/loss? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
B.3 **Brussels:** Have you had a grant for an energy audit or advice financed by the Brussels region? If yes, when? **Walloon:** Have you had any energy audit (AMURE) or advice financed by the Walloon region? If yes, when? **Flanders:** Have you received any advice or energy audit financed by VLAO (Vlaams Agentschap Ondernemen)? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
B.4 **Brussels:** Have you benefited from an investment subsidy from the Brussels region for improving your building's or production process's energy efficiency ? If yes, when? **Walloon:** Have you had a grant from the energy fund of the Walloon region for improving your building's or production process's energy efficiency? If yes, when? **Flanders:** Have you received an ecological grant (Ecologipremeie) of the Flemish region for improving your building's or production process's energy efficiency? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
B.5 **Flanders:** Do you have a heat and power certificate from the Flemish region (warmtekrachtcertificaat)? If yes, since when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
FRANCE		
F1. Are you part of the AERES (Association des entreprises pour la réduction de l'effet de serre) and have signed up to voluntary GHG emission reductions? If yes, since when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
F2. Have you had a grant for an energy audit or advice financed by ADEME? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
F3. Have you benefited from a "FOGIME" guarantee for loans you have taken to invest into energy efficiency improvements or emission reductions ? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
F4. Have you benefited from a grant from ADEME for improving your building's or production process's energy efficiency ? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
GERMANY		
G.1 Renewable Energy Sources Act		
(a) In previous year, have you been granted a discount on your energy cost which reduces the energy cost apportionment embodied in the Renewable Energy Sources Act?	no, yes, dk, rf, na	
(b) Have you applied for the discount (also) in 2009?	no, yes, dk, rf, na	
(c) Did the certification process require you to upgrade your energy management system? *Note: Since 2009 the approval of the discount is subject to the certification of your energy management system by 30 June 2009.*	yes, no upgrade necessary, no had certificate before, dk, rf, na	
G.2 Public support programmes		
Have you participated in public support programs aimed at saving energy or at reducing GHG emissions?	no, list of years 2001-2009, yes dk year. dk, rf, na	Climate initiative
	no, list of years 2001-2009, yes dk year. dk, rf, na	ERP Environment and Energy Efficiency Programme
	no, list of years 2001-2009, yes dk year. dk, rf, na	Grant for independent energy audit from fonds for energy efficiency in SME
	no, list of years 2001-2009, yes dk year. dk, rf, na	Provision of cut-rate investment credit from fonds for energy efficiency in SME to implement identified energy-saving measures
	no, list of years 2001-2009, yes dk year. dk, rf, na	Support scheme of a federal state
	text	Other

Questions	Values	Coding description
HUNGARY		
H1. Have you received government support for any of your investments to reduce emissions or implement energy efficiency measures or increase the use of renewables? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	Környezetvédelmi Alap Célelőirányzat
H2.(a) Have you received EU funds to support any of your investments to reduce emissions or implement energy efficiency measures or increase the use of renewables? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
(b) If yes, for which Operative Program; which call for proposal?	KEOP, KIOP, ERFA, dk, rf, na	
H3. Have you received funding from the Norwegian Fund for support? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	EGT és Norvég Finanszírozási Mechanizmusok program
POLAND		
P.1 Do you use the sectoral information brochures published by the Ministry of Environment that include the information about the best available technologies for different economic activity? Since when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
P.2 Have you ever taken a technological credit provided by the Technological Credit Fund? If yes. when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
P.3 Have you ever been co-financed or have taken a preferential credit from the National Fund of Environmental Protection and Water Management, Bank of Environmental Protection and EkoFund? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	
P.4 Have you ever benefited from the subventions and tax reductions from the government for environmental purposes? If yes, when?	no, list of years 2001-2009, yes dk year. dk, rf, na	

Questions	Values	Coding description	
VIII. Post Interview			
Interview duration (mins)	number	Minutes	
Interviewers' impression of interviewee's reliability	1-5, dk, rf	Low	Some knowledge about his site, and no knowledge about the rest of the firm.
		Mid	Expert knowledge about his site, and some knowledge about the rest of the firm.
		High	Expert knowledge about his site and the rest of the firm.
Interviewee seemed concerned about climate change	1-5, dk, rf	Low	Not concerned.
		Mid	Somewhat.
		High	Very concerned.
Interviewee seemed skeptic about action on climate change	1-5, dk, rf	Low	Not skeptic at all.
		Mid	Somewhat skeptic.
		High	Very skeptic.
Mentioned other climate change related policies	text		
Moaned a lot about high energy prices	no, a little, a lot		
Number of times interview needed to be rescheduled	number		
Seniority of interviewee	Director, VP/General Manager, Plant/Factory Manager, Manufacturing/Production Manager, (Environmental), Health & Safety Manager, Technician		
Age of interviewee *Note: Do not ask, guess!*	number		
Gender of interviewee	male, female		
Interview language	English, French, German, Dutch, Hungarian, Polish		