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Industry Compensation under Relocation Risk: A Firm-Level Analysis of the EU Emissions Trading Scheme†

By Ralf Martin, Mirabelle Muûls, Laure B. de Preux, and Ulrich J. Wagner*

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. (*JEL* H23, Q52, Q53, Q54, Q58)

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

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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 reelection 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 countries have implemented carbon taxes since the 1990s, 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 policymaking in the European Union.

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

[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 (forthcoming) 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, location 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

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 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 6 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 percent 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 canceled 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]

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.

[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 (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 United States at between 8 and 32 percent of the associated earnings.

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 worldwide. Specifically, Australia, California, Republic of 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 policymaking 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 II describes the dataset, particularly how we measure firm-level vulnerability to carbon pricing. Section III presents a normative framework for optimal permit allocation under relocation risk and conducts several counterfactual experiments under alternative constraints. Section IV concludes.

I. 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 microallocation 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 canceled.

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.

A. *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 percent best performing installations in the European Union 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

$$(1) \quad q^b_{ijt} = benchmark_j \cdot historical\ activity\ level_{i,j} \cdot reduction_{j,t} \cdot correction_t.$$

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 permits resulting from the first two terms in equation (1) is scaled by two factors. First, the

[5] Ellerman, Buchner, and Carraro (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).

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 subinstallations 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 percent relative to the historical activity level, a 50 percent reduction is applied to the free allowance allocation. If activity falls below 90 percent, 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 percent 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 decisions (Ellerman 2008; Meunier, Ponssard, and Quirion 2012).

B. *Free Allocation to Sectors Deemed at Risk of Carbon Leakage*

The gradual reduction in free allowances from 80 percent to 30 percent was met with strong opposition from carbon-intensive industries, who convinced EU lawmakers 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 percent 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

[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); Fischer and Fox (2007); Fowlie (2011); and Bushnell and Chen (2012). Monjon and Quirion (2011) analyze a hypothetical output-based updating rule for the EU ETS.

[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).

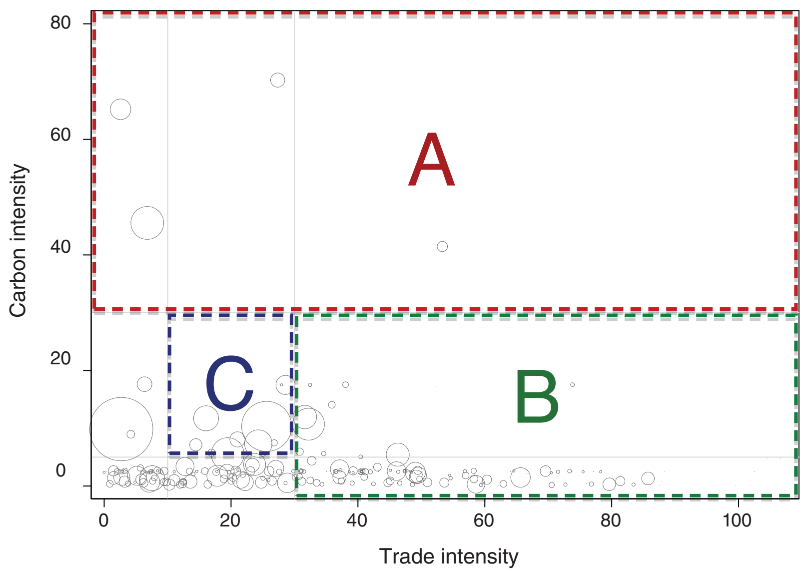

Figure 1. Sectors Exempt from Permit Auctions

Notes: The figure shows a scatter plot of the carbon and trade intensities of four-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.

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/$t CO_2$). 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)" (European 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 percent and their TI is greater than 10 percent, or either CI or TI is greater than 30 percent. 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 three-digit sectors in a diagram with CI on the vertical 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

[9] They are calculated as electricity consumption (in megawatt-hours (MWh)) multiplied by the average emission intensity of electricity generation in the EU27 countries (0.465 $t CO_2$ /MWh), and applying the same proxy price for an European Union Allowance of €30/$t CO_2$.

[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.

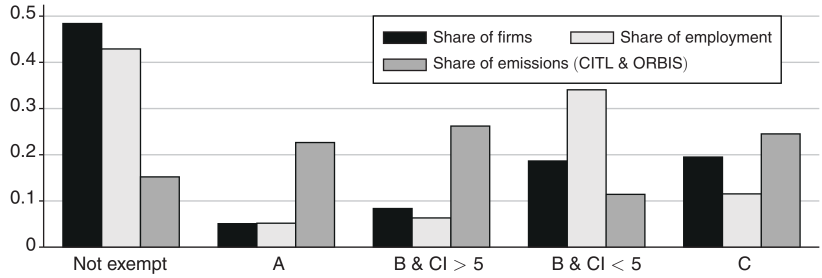

FIGURE 2. RELATIVE SIZE OF THE EXEMPTION GROUPS

Notes: The figure 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 3,247 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 (Community Independent Transactions Log). To compute CI and TI figures at the NACE four-digit level, we follow the methodology and databases used by the European Commission (2009).

(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 percent.[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]

C. *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

[11] Figure E.2 in the online Appendix compares the size of these groups across different samples, namely: (i) all EU ETS firms in the CITL/ORBIS matched sample; (ii) all such firms in the six countries where we interviewed firms; and (iii) 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. A study by Juergens, Barreiro-Hurlé, and Vasa (2013) finds a share of 23 percent.

[13] In a companion paper, we analyze the empirical content of the carbon leakage criteria in more detail (Martin et al. forthcoming).

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 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, Ndoye, and Zachmann 2011; Bushnell, Chong, and Mansur 2013; Chan, Li, and Zhang 2013; Commins et al. 2011; Petrick and Wagner 2014; Wagner et al. 2013). These studies use a broad set of indicators to analyze intensive-margin adjustments to production, employment and productivity (for a survey, see Martin, Muûls, and Wagner 2013).

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, Goulder, and Gurney 2005; Bovenberg, Goulder, and Jacobsen 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 et al. 2010; Martin et al. 2012).

II. Data

This paper combines three principal sources of data into a unique firm-level dataset 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 practices relating to climate policy more generally—by interviewing managers of manufacturing firms in six European countries: Belgium, France, Germany, Hungary, Poland, and the United Kingdom.[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 data from EUROSTAT are used to calculate carbon emissions, CI, and TI

[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.

[15] While theoretical and simulation-based studies find a negative impact of the EU ETS on production in most manufacturing industries (e.g., Reinaud 2005; Demailly and Quirion 2006, 2008; 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.

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

at the sector level. This section describes the data collection and matching processes and summarizes our core dataset.

A. *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 percent 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, French, and Polish firms more strongly than British, Belgian, and Hungarian firms (cf. panel A of Figure 3). However, in no country does the 95 percent confidence band include outsourcing of more than 10 percent of production in response to regulation. Looking across different industries, fuels and other minerals, glass, iron, and steel are the most vulnerable (cf. panel B of Figure 3). 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 percent confidence interval.[18]

Further results (reported in online 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 and steel, and cement are the most vulnerable industries, irrespective of employment size. Other energy-intensive industries such as food and tobacco, fabricated metals, and vehicles are significantly less vulnerable than the average.

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

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

[19] The regressions underlying online Appendix 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).

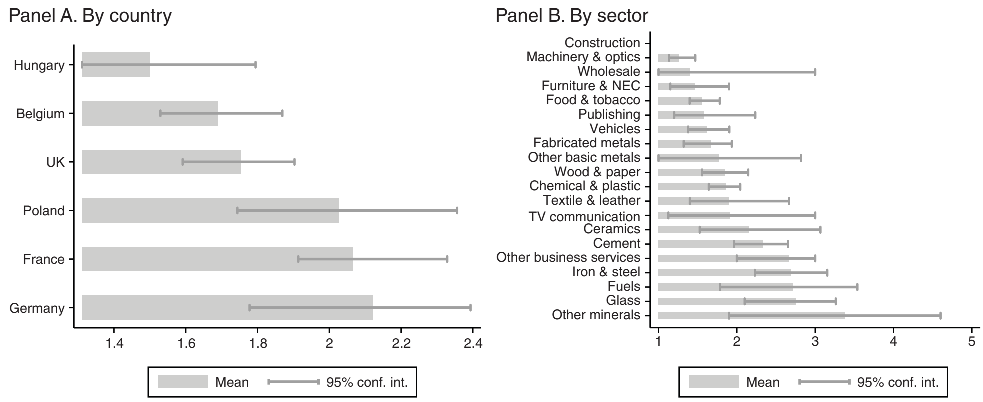

Figure 3. Average Vulnerability Score by Country and Industry

Notes: The bars show the average score in a given country (panel A) or three-digit sector (panel B). Bootstrapped confidence bands are calculated at the 95 percent level. NEC: Not elsewhere classified.

B. *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 (Organisation for Economic Co-operation and Development) 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 dialogue with specific questions for discussion. On the basis of this dialogue, 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 managements' 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]

[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).

For consistency checks of interviewer scoring, a subset of randomly selected interviews were double-scored by a second team member who listened in.

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 percent and 70 percent of managers contacted in each country worked at an EU ETS firm. In total, we contacted 1,451 firms in the 6 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 United Kingdom). Of all firms we interviewed, 446 (57 percent) were in the EU ETS. In spite of a relatively high response rate of 53 percent (68 percent among EU ETS firms and 39 percent 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 online 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 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

[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).

Table 1—Correlations between Vulnerability Score and Other Interview Variables

	All firms (1)	EU ETS firms (2)
Cost pass-through (percent)	−0.107***	−0.109*
Share of non-EU competitors (percent)	0.141***	0.135**
Non-EU competitors	0.02	−0.06
Total competitors	0.02	−0.14
Share of sales exported to non EU (percent)	−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***	0.16***
Enforcement of targets (S)	0.12***	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 whereas those in column 2 are calculated using only firms in the EU ETS.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

the difference between energy prices at home and abroad, using more than 460,000 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 online 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

[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.

TABLE 2—ENERGY-PRICE ELASTICITY OF EMPLOYMENT IN VULNERABLE SECTORS

	Employment			
	OECD		European Union	
	(1)	(2)	(3)	(4)
Employment_{t-1}	0.966***	0.966***	0.950***	0.949***
	(0.006)	(0.006)	(0.007)	(0.007)
Relative Energy Price $[\text{EP}^D - \text{EP}^F]$	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 online 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 estimator by Blundell and Bond (1998). Robust standard errors, clustered at the firm level, are in parentheses.

***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

the employment response to an increase in the energy price differential decreases with the sector's VS. For instance, column 1 of Table 2 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 percent 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 of Table 2 are very similar. 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.

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

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 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 online Appendix B.2.

C. *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 online 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 of 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 allocated 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.[26]

[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 percent 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.

[26] We thank Oliver Sartor, Stephen Lecourt, and Clément Pallière for kindly providing us with the data for 20 of these countries, for which they collected and matched the NIM data on free permit allocation to ORBIS (see Sartor, Pallière, and Lecourt forthcoming). We complemented this dataset with the NIM data for Belgium and Hungary, which we matched to ORBIS by hand. In total, this results in a sample of nearly 8,000 installations covering 95 percent of the emissions.

Table 3—Firm Characteristics

	Mean	Standard deviation	Percentiles			Observations
			Tenth	Fiftieth	Ninetieth	
Firm						
Age (years)	37	37	7	22	87	736
Turnover (millions €)	478	2,790	10	77	728	696
Number of employees	1,004	3,891	84	298	1,890	699
EBIT (millions €)	17	78	−2	2	42	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 (millions US$)	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).

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 United Kingdom) 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 four-digit NACE industrial sectors.[27] 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 (forthcoming).[28] This allows us to match 75 percent of CITL installations and 76 percent of surrendered CO_2 allowances. NACE rev 1.1 classification and employment data is available for 3,247 firms, 74 percent of which are manufacturing firms. Table E.1 of the online Appendix summarizes the correspondence between sectoral classifications.

III. 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.[29] 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.

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

[28] 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.

[29] Since the capacity-based updating in phase III does not affect short-run production choices (cf. Section IA 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 online Appendix D.

A. *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 i.i.d. 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 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

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

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 nonregulated 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.[30]

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 $\bar{Q}$:

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

[30] 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.

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

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

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.

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 $\overline{R}$:

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

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.

B. *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.[31]

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 $V_{i+1}(s_i - q_i)$ is the value of leaving $s_i - q_i$ permits to all remaining firms in

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

the sequence. It is straightforward to solve equation (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 equation (3) to get $q_i = \pi_i^{-1}\Big[-F_i^{-1}\Big(\frac{r_i}{\alpha l_i + (1-\alpha)e_i}\Big)\Big]$. 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

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

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 $\pi_i(q_i) = \delta_{0i} + \delta_{1i}\,q_i$.[32] This yields the relocation probability

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

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 percent of its emissions at no cost.[33] For a given mapping from the VS into relocation probabilities,[34] this allows us to evaluate the relocation probability with no free permits, $\Pr_i(y_i = 1\,|\,q_i = 0)$ as well as with 80 percent free permits $\Pr_i(y_i = 1\,|\,q_i = 0.8e_i)$ and use these to back out the parameters $\beta_{0i} = \ln\Big[\frac{1-\Pr_i(y_i=1\,|\,q_i=0)}{\Pr_i(y_i=1\,|\,q_i=0)}\Big]$ and $\beta_{1i} = \frac{1}{0.8e_i}\ln\Big[\frac{1-\Pr_i(y_i=1\,|\,q_i=0.8e_i)}{\Pr_i(y_i=1\,|\,q_i=0.8e_i)} - \beta_{0i}\Big]$ in equation (9).

C. *Simulation of Counterfactual Allocations*

We compute optimal allocations under different assumptions about the government's objective function (risk versus cost minimization), about the damage weights

[32] 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.

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

[34] 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 0.55 to scores 2 and 4, respectively.

Table 4—Risk of Job Loss and Carbon Leakage

	Actual risk	Minimized risk		Change in risk	
Reference scenario	(1)	(2)	(3)	(4)	(5)
Panel 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]
Panel 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 ninety-fifth percentiles in brackets, obtained from a nonparametric bootstrap with resampling.

(job loss versus 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 in Table 4 shows that job risk under grandfathering can be reduced from 4.2 percent to 2.9 percent of employment in EU ETS sectors when permits are allocated optimally across firms. With benchmarking, job risk increases by two-thirds to 6.9 percent of ETS employment. Optimal redistribution of permits to firms brings the risk back down to 2.9 percent. To account for sampling error surrounding these point estimates, we report the bootstrapped ninety-fifth percentile of each statistic in brackets. This shows that the risk to jobs amounts to at most 4.7 percent 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 probability 0.95.

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 percent is higher than the job risk, increases by almost half to 22.8 percent under benchmarking. Efficient allocation reduces the leakage risk to just above 13 percent 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 probability 0.95.

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 four-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.[35] While sector-level allocation still reduces job risk compared to benchmarking—at least 0.5 percentage points with probability 0.95, and 2.4 percentage points on average—this is not guaranteed anymore for CO_2 risk. In fact, the ninety-fifth percentile of the risk change reported in column 5 of Table 4 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 taxpayer'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 percent and 24.5 percent of permits for free, depending on whether job risk or carbon leakage risk is held fixed.[36]

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 percent 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 percent 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 percent 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 probability 0.95, the level of job risk induced by the benchmarking rules could be achieved by allocating at most 7.0 percent of the permits for free. The corresponding figure for carbon leakage risk is 22.3 percent. This means that EU governments could raise additional revenue by auctioning a much

[35] The constraints on the number of free permits are binding now because grandfathering individual 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.

[36] 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 percent of total emissions*)

	Actual	Minimized allocation	
Scenario	(1)	(2)	(3)
Grandfathering	100.0	14.3 [31.4]	24.5 [39.2]
Benchmarking	52.3	1.6 [7.0]	13.0 [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 ninety-fifth percentile of the permit share, obtained from a nonparametric bootstrap with resampling, is reported in brackets.

larger amount of emissions permits instead of allocating them free, without increasing the expected cost of carbon leakage or job loss.[37]

D. *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 $\overline{Q}$, an allocation share $\theta_i = f(\mathbf{x}_i; \boldsymbol{\gamma})$ maps a vector $\mathbf{x}_i = \left(x_i^1, \ldots, x_i^k\right)$ of k observable characteristics for firm i into the unit interval. Suppose that the function $f(\cdot)$ is known up to a parameter vector $\boldsymbol{\gamma}$. Substituting $\hat{q}_i = \theta_i \overline{Q}$ into the risk minimization program (4) yields

$$(10) \qquad \min_{\boldsymbol{\gamma}} \sum_{i=1}^{n} r_i \left(f(\mathbf{x}_i; \boldsymbol{\gamma})\overline{Q}\right) \quad \text{s.t.} \quad \sum_{i=1}^{n} f(\mathbf{x}_i; \boldsymbol{\gamma}) = 1 \wedge f(\mathbf{x}_i; \boldsymbol{\gamma}) \geq 0 \quad \forall i.$$

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, $f(\mathbf{x}_i; \boldsymbol{\gamma}) = \frac{\prod_k \left(x_i^k\right)^{\gamma_k}}{\sum_{j=1}^{n} \prod_k \left(x_j^k\right)^{\gamma_k}}$, which generalizes, e.g., grandfathering of historic emissions e_i (that is, $f(e_i; \gamma_e) = (e_i^{\gamma_e}) / \left(\sum_j e_j^{\gamma_e}\right)$ and $\gamma_e = 1$) to the case of

[37] 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. forthcoming).

Table 6—Feasible Optimal Allocation Rules

	Minimizing expected job loss				Minimizing expected carbon leakage	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Parameter estimates $\hat{\gamma}$						
Benchmarking allocation	0.44				1.13	
	[0.23, 0.94]				[0.83, 1.27]	
CO_2 emissions		0.63	0.58	0.63		1.02
		[0.51, 0.85]	[0.39, 0.78]	[0.50, 0.82]		[0.85, 2.66]
Employment		0.23	0.29			−0.20
		[0.11, 0.40]	[0.12, 0.57]			[−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 percent of total ETS employment or emissions)						
Job risk	5.54	4.61	4.51	4.58	8.21	9.14
	[9.05]	[7.14]	[6.73]	[7.29]	[12.08]	[15.51]
Δ	−1.39	−2.31	−2.41	−2.35	1.28	2.22
	[−0.09]	[−0.74]	[−0.88]	[−0.73]	[2.71]	[7.09]
CO_2 risk	29.66	26.73	26.05	25.43	22.12	23.22
	[39.53]	[37.61]	[35.50]	[36.14]	[32.33]	[31.78]
Δ	6.88	3.94	3.27	2.64	−0.67	0.44
	[13.17]	[8.86]	[8.25]	[8.00]	[−0.01]	[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 percent of employment at all firms in the sample) and leakage (in percent 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 four-digit industry level. The numbers in brackets report two-sided 95 percent confidence intervals of the coefficient estimates in panel A and the ninety-fifth percentiles of the risk statistic in panel B, obtained from a bootstrap with 100 replications.

multiple variables. We solve for γ using a standard maximum likelihood solver where $r_i\left(f(\mathbf{x}_i;\gamma)\overline{Q}\right)$ corresponds to the likelihood contribution of observation i.

Table 6 reports the solution vector $\hat{\gamma}$ for $\mathbf{x}$-vectors of varying lengths (panel A) along with the associated risk of job loss and carbon leakage (panel B). We hold $\overline{Q}$ fixed at the total amount of permits allocated for free during phase III; i.e., $\overline{Q} = \sum_i q_i^b$, 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 $\hat{\gamma}_b < 1$, risk can be reduced by shifting permits from firms that receive more permits to those that receive less, and vice versa if $\hat{\gamma}_b > 1$. When minimizing job risk, we obtain a point estimate of $\hat{\gamma}_b = 0.44$, which is smaller than 1 at the 5 percent 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 of Table 6 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 percent of the gap to the unconstrained minimum of 2.9 percent of all jobs in EU ETS firms.[38] Compared to column 1 of Table 6, 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.[39] Finally, measuring firm size in terms of turnover rather than employment (in column 4) yields results virtually identical to those in column 2 of Table 6.

Feasible optimal allocation rules for minimizing CO_2 risk are reported in columns 5 and 6 of Table 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 of Table 6, where we include firm-level employment and CO_2 in the allocation function.[40]

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.

IV. 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.

[38] Panel B of Table 6 reports a reduction by at least 0.7 percent of EU ETS employment in 95 out of 100 bootstrap replications.

[39] We use TI with less-developed countries because we find it to be more correlated with the VS than the overall TI used by the Commission. See Martin et al. (forthcoming) for an in-depth discussion of these correlations.

[40] We do not find a significant reduction of CO_2 risk when including trade and carbon intensity as in column 3, either of Table 6. These results are available on request.

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 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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