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QUADERNI DEL DIPARTIMENTO
DI ECONOMIA POLITICA E STATISTICA

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n. 861 – Ottobre 2021

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Abstract

We develop a new measure of installation-level environmental compliance costs under an Emissions Trading System (ETS) by estimating normalized demand curves of permits sector-by-sector. Our measure reflects installation-level compliance costs deviations within-sector and it is scaled by both the installation's baseline output and the sector-specific abatement efficiency. An application to four sectors in Phase 3 of the EU ETS unveils a non-negligible within-sector variance and reveals that the installation-level dimension explains the largest part of it, while the country effect accounts for 7.7% to 11.4% of the total within-sector variance. This points to the installation-level dimension as mostly important when the impact of environmental regulations has to be assessed in practice.

Keywords: compliance costs, environmental regulation, abatement technology, EU ETS.

J.E.L. Classification: L50, L60, Q52, Q58

Acknowledgements: We thank Sylwia Bialek, Simone Borghesi, Ralf Martin, Simona Mateuţ, Fabian Naumann, Simon Quemin, Piercarlo Zanchettin and participants at the 2019 EAERE Conference (Manchester), the 3rd International Workshop of Climate Change and Sustainability (Bologna, 2019), the 2020 NERI Workshop (Naples), and the 2020 IAERE Conference (Brescia) for useful comments and discussions. Any errors are our own.

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1 Introduction

Covering around 10,000 installations in 30 countries, the European Union Emissions Trading System (EU ETS) which started in 2005 is the world's largest cap-and-trade program and is acknowledged as one of the most important market-based applications of economic principles to the climate change challenge (Ellerman et al., 2016). Each installation under the EU ETS is required to possess an allowance for each ton of CO_2-equivalent that it emits and is allowed to trade allowances on a competitive market. As the pursuit of profits leads firms to equate their own marginal abatement costs to the allowance price, differences in the abatement costs functions across firms will reflect into differences in firms' compliance costs, i.e. in the total costs borne by each firm to comply with the regulation.

In this paper, we introduce an installation-level measure that can be used to compare total environmental compliance costs of polluting installations under the EU ETS both across and within sectors and countries. There are two key motivations for creating this measure.

First, estimating compliance costs is essential to gauging the extent to which environmental regulation actually bites polluting firms and to evaluate the effects of policy stringency (Brunel and Levinson, 2016). Commonly used indicators at the country or regional level are based on aggregate pollution abatement costs and expenditures, with adjustments for industrial composition (Keller and Levinson, 2002) or without (Friedman et al. 1992; Co and List, 2000). Others in the literature have proposed a sectoral approach based on comparison of emissions and allowances (e.g., Levinson, 2001; Borghesi et al., 2015). Yet, these measures fail to allow for cross-installation variation within countries and sectors and hence have limited applicability when one wants to assess the firm-level effects of environmental regulation. The firm-level perspective is important as it helps dealing with often-raised questions about the impact of environmental regulations on a number of firm-level outcomes, including firm innovation, productivity and comparative advantages. In particular, a body of recent research examines how environmental regulations influence international trade, outsourcing and offshoring (Cherniwchan et al., 2017). Because empirical work linking trade to the environment largely exploits plant-level observations, this level of detail seems unavoidable also as far as the measurement of the stringency of environmental regulations is concerned.

Secondly, the information provided by compliance costs contributes to document the heterogeneity of the abatement technologies across production units. Conventional attempts to model and estimate abatement technologies at the installation level follow an engineering approach, which relies on subjective evaluations of engineering experts (Pizer and Kopp, 2005). This approach, however, can be problematic when applied on a broad scale, because it requires information on specific characteristics of individual plants, unless one makes strong assumptions about the degree of technological sharing across firms.

We provide an installation-level measure of compliance costs, using only data on installations' allowances and emissions. By manipulating the residuals of normalized allowance demand regressions estimated sector-by-sector, we obtain a measure of the difference between the installation's compliance costs and the average (estimated) compliance costs within the sector. The advantage of this strategy consists in providing a scaled measure of compliance costs which both allows for making cross-sector comparisons between installations and fully incorporates installation-specific abatement efficiency (this possibly reflecting also group-specific – e.g. country-specific – components), without requiring additional data on abatement expenditures or information on the technologies used. While the method to obtain the measure can be easily generalized to any tradable permits program, in this paper we propose a version tailored to the EU ETS.

An application to four sectors in EU ETS Phase 3 over the years 2013 through 2019 reveals that the within-sector variation of compliance costs across installations is large, whereas the country effect only accounts for roughly 7.7% (11.4% when time-varying country effects are also included) of the total within-sector variance. This points to the importance of the installation dimension when compliance costs are to be measured under a same environmental policy across countries.

The remainder of the paper is structured as follows. In Section 2, we present the basic notation and the empirical construction of the measure, obtained as compliance costs deviations. In Section 3, we report the results of the empirical exercise on installation-level data from the EU ETS Phase 3. Section 4 concludes.

2 The empirical model

2.1 Definition of terms

Let X_{its} and Y_{its} be, respectively, the emission and output levels of installation i operating in sector s in year t, and x_{its} be the corresponding emission-to-output ratio (or emission intensity). We express abatement in terms of reduction in the emission intensity and define it as $a_{its} = \bar{x}_{its} - x_{its}$, where $\bar{x}_{its}$ is the Business-As-Usual (BAU) emission intensity in the absence of abatement, with $x_{its} \leq \bar{x}_{its}$.

Total compliance costs for installation i operating in sector s in year t are defined as follows:[1,2]

$$C_{its} = \frac{Y_{its}}{2\mu_{is}} a_{its}^2 + P_t D_{its} \tag{1}$$

where μ_{is} is an abatement efficiency parameter, P_t is the allowance price, and D_{its} is the demand for allowances. The first term on the right hand side of (1) is the cost of abatement implying that the greater the output level, the greater the cost of reducing the emission-to-output ratio; the second term represents the costs of buying or the revenue of selling allowances. The net demand for allowances is:

$$D_{its} = Y_{its}(\bar{x}_{its} - a_{its}) - \hat{X}_{its} \tag{2}$$

[1] This can be seen as a variant of the model in Cherniwchan et al.'s (2017) Supplemental Appendix, with a single intermediate good (which is then also the final good), $a_j \to 0$ and $\gamma b^{(1-\delta)/\delta}$ normalized to one in their equation (1). Then, normalizing our $\bar{x}_{its}$ to one and generalizing the $g(A)$ function in Cherniwchan et al.'s (2017) Supplemental Appendix equation (2) to $g(A, x)$, our model features $g(A, x) = 1 - \sqrt{2\mu A/x}$.

[2] We do not include transaction costs of inter-firm trade (Baudry et al., 2021), because we do not have installation ownership data.

with $\hat{X}_{its}$ being the number of allowances allocated to installation i in year t. If D_{its} is negative, the installation is selling allowances.

The optimal choice for each installation given Y_{its} is to reduce the emission intensity to the point where the marginal cost of abatement is equal to the marginal net benefit of trading allowances. Under this condition compliance costs C_{its} in (1) are minimized and the optimal level of a_{its} is:

$$a^*_{its} = \mu_{is} P_t \tag{3}$$

2.2 Measuring compliance costs deviations

From Phase 3 (2013-2020) onwards, the EU ETS has used the following allowance allocation rule:

$$\hat{X}_{its} = \tilde{x}_s f_s k_t Q_{is} \tag{4}$$

where $\tilde{x}_s$ is the sectoral benchmark emission intensity, f_s represents the carbon leakage exposure factor (CLEF) and k_t is the cross-sectoral correction factor (CSCF),[3] and the baseline activity level Q_{is} is the 2005-08 median level of output.

We shall proxy each installation's output Y_{its} by its baseline activity Q_{is}:

$$Y_{its} = Q_{is} = \frac{\hat{X}_{its}}{\tilde{x}_s f_s k_t} \tag{5}$$

where the second equality follows from (4). Since all the terms on the RHS of (5) can be observed,

[3]The CLEF determines the fraction of benchmark emissions that the installation receives for free. The Commission has compiled a list of sectors that it deems at significant risk of carbon leakage. These include all four sectors that we analyze in this paper. Installations in these sectors receive all of their benchmark emissions for free (CLEF = 1). All other sectors received 80% for free in 2013, declining linearly to 30% in 2020. The total amount of free allowances calculated in this way might exceed the overall cap for the non-electricity sectors. The CSCF makes sure that this does not occur.

we can infer Q_{is}. Substituting (3) and (5) into (2), the demand for allowances can be expressed as:

$$D_{its} = Q_{is}(\bar{x}_{its} - \mu_{is}P_t) - \hat{X}_{its} \tag{6}$$

Normalizing (6) by Q_{is} yields:

$$d_{its} \equiv \frac{D_{its}}{Q_{is}} = \bar{x}_{its} - \mu_{is}P_t - \hat{x}_{ts} \tag{7}$$

where from (5), allowance allocation $\hat{x}_{ts}$ per unit of output is:

$$\hat{x}_{ts} \equiv \frac{\hat{X}_{its}}{Q_{is}} = \tilde{x}_s f_s k_t \tag{8}$$

In the EU ETS, we observe D_{its} and P_t, while Q_{is} can be obtained from (5) and $\hat{x}_{ts}$ from (8). As for the other two parameters in (7), we shall assume that BAU emission intensity $\bar{x}_{its}$ is the same for all installations in the sector:

$$\bar{x}_{its} = \bar{x}_s \tag{9}$$

and we decompose μ_{is} in (7) into a sector-specific average μ_s and an installation-specific deviation η_{is}, that is:

$$\mu_{is} = \mu_s + \eta_{is} \tag{10}$$

Using (9) and (10), we can then rewrite (7) for the purpose of estimation as:

$$demand_{its} = constant_s + \beta_s P_t + \gamma_s allocation_{ts} + \varepsilon_{its} \tag{11}$$

where we denoted d_{its} by $demand_{its}$ and $\hat{x}_{ts}$ by $allocation_{ts}$. In (11), $constant_s = \bar{x}_s$, $\beta_s = -\mu_s$, $\varepsilon_{its} = -\eta_{is}P_t$ and we expect $\gamma_s = -1$. Since the values of $demand_{its}$, $allocation_{ts}$ and P_t are known, $constant_s$, β_s and γ_s in (11) can be estimated by means of ordinary least squares (OLS), with (11) run sector-by-sector.

Substituting (3), (5), (7) and (9) into (1) and scaling by Q_{is}, we obtain the normalized compliance cost of installation i:

$$c_{its} \equiv \frac{C_{its}}{Q_{is}} = P_t(\bar{x}_s - \hat{x}_{ts}) - \frac{1}{2}\mu_{is}P_t^2 \tag{12}$$

Note that μ_{is} is the sole variable identifying installation i within its sector. Therefore, using (10), sector-average normalized compliance costs are:

$$c_{ts} = P_t(\bar{x}_s - \hat{x}_{ts}) - \frac{1}{2}\mu_s P_t^2 \tag{13}$$

By (10), (12) and (13), the difference between installation i's normalized compliance costs and its sectoral average (i.e. installation i's compliance costs deviation) is:

$$\Delta c_{its} \equiv c_{its} - c_{ts} = -\frac{1}{2}\eta_{is}P_t^2 = \frac{1}{2}\varepsilon_{its}P_t \tag{14}$$

where the final equality follows from $\eta_{is} = -\frac{\varepsilon_{its}}{P_t}$.

3 Estimation

While in principle our method can be applied to the entire universe of installations under the EU ETS, we propose an empirical exercise on a subset of sectors for which data on product-specific benchmark emission intensity can be matched with the sectoral classification of installation-level data provided in Operator Holding Accounts (EU ETS Database, 2020) maintained by the Environment Directorate-General of the European Commission.

We estimate the normalized demand parameters $constant_s$, β_s and γ_s in (11), sector-by-sector, using installation-level data on emissions and allocated allowances for installations operating in the production of ammonia, aluminium, lime and dolomite, and glass. We restrict our analysis to the EU

ETS Phase 3, over the years 2013 to 2019.[4] The average annual allowance price languished between €4.45 and €7.69 from 2013 through 2017, before rallying to €15.88 in 2018 and €24.84 in 2019. As a cleaning procedure, we drop from the sample installation-year observations below the 1$^{\text{st}}$ and above the 99$^{\text{th}}$ percentile of the distribution of d_{its} within each sector.

Figure 1 shows the probability density functions, obtained by means of kernel density estimation, of the normalized demands of allowances in each sector. In all the sectors, the density patterns reveal an increasing dispersion of normalized demand over time in Phase 3.

[insert Figure 1 about here]

Equation (11) is estimated sector-by-sector by means of OLS, with heteroskedasticity robust standard errors being clustered at the country level. Estimated parameters are collected in Table 1.

[insert Table 1 about here]

As expected, we obtain negative and significant price parameters, while the constant term is always positive and significant. Since the coefficients are computed with respect to the median value of each associated variable in each sectoral sub-sample, and given that the allowance price is the same for all the installations, the magnitudes of the price parameter across sectors can be compared. This reveals that the association between price and normalized demand varies evidently across sectors. Similarly, the root mean squared error (Root MSE), expressing the variation of the residuals in the model, also shows considerable cross-sector heterogeneity. Interestingly enough, this heterogeneity does not seem to follow the size of the sectoral sub-samples.

We tested the hypothesis that the parameter associated with $allocation_{ts}$ (i.e., γ_s) is -1 and find that the null hypothesis cannot be rejected at a conventional level of significance in all the sectors,

[4]We exclude data from 2020 because of the Covid-19 outbreak.

coherently with our theoretical model.

We then compute our measure of compliance costs deviations Δc_{its} as the difference between installation i's normalized compliance cost and the sector average as in (14).

By construction, the measure is scaled by both the installation's baseline output and the sector-specific abatement efficiency (reflecting the technological dimension common to all the installations in the sector). Hence, values of the measure for installations belonging to different sectors can be pooled. Reassuringly, Figure 2 shows that the measure is approximately normally distributed both for the pooled sample and for each sector. This reflects the basic mechanism behind our empirical strategy, with installation-level compliance costs deviations being obtained from a manipulation from the sector-by-sector OLS regression residuals.

[insert Figure 2 about here]

To give a sense of scale of how cross-country and time variation compares with installation-level variation, in Table (2) we report the result of a simple exercise of variance decomposition. First, we calculated the total variance of Δc_{its} (reported in row (A) of Table (2)) for each sector (from column [1] to [4] of Table (2)) and for the pooled sample (column [5]), and normalized it to 100. Second, we obtained the share of the total variance purged of country effects (row (B) of Table (2)), time effects (row (C)), country and time effects (row (D)), and country, time and country-time effects (row (E)). As for the pooled sample, we find that the compliance costs' variance purged of country effects amounts to 92.3% of the total (within-sector) variance. When time effects are absorbed, the change in the residual variance is hardly noticeable. When compliance costs deviations are also purged of country-specific time effects (i.e. country×year effects) that absorb idiosyncratic shocks at a country-level, the residual variance reduces to 88.6%. Some differences in the results emerge from sector-specific variance decompositions: in particular, country, time and country-time effects explain about 47.3%, 15.3%, 20.9% and 32.4% of the total variance in the production of ammonia, glass, aluminium and lime and dolomite, respectively, against the 11.4% in the pooled sample.

Taken together, these pieces of evidence suggest that the installation-level dimension explains most of the heterogeneity in compliance costs across production units, while the residual component (i.e. the country and time dimensions) accounts for a small part of it. To help intuiting that the dispersion of compliance costs deviations is mostly across installations, in Figure 3 we plot the within-country distributions of Δc_{its}, averaged over Phase 3.

[insert Figure 3 about here]

4 Conclusion

We have proposed a new method for measuring environmental compliance costs at the level of individual installations. An application of our measure to four sectors under the EU ETS unveils a non-negligible within-sector variance and reveals that the installation-level dimension accounts for the largest part of it, while the country dimension is much less relevant. This points to the installation-level dimension as most important when the impact of environmental regulations has to be assessed in practice.

Our study motivates future research on the determinants of compliance cost heterogeneity across installations within sectors and countries.

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Table 1: Estimated parameters of normalized demand functions, by sector.

	[1] AMMONIA	[2] GLASS	[3] ALUMINIUM	[4] LIME AND DOLOMITE
$constant_s$	1.421**	0.346***	1.923***	1.020**
	(0.044)	(0.001)	(0.274)	(0.380)
P_t	-0.012**	-0.001***	-0.006*	-0.006**
	(0.004)	(0.000)	(0.003)	(0.003)
$allocation_{ts}$	-0.974***	-0.799***	-1.263***	-0.944**
	(0.306)	(0.120)	(0.274)	(0.342)
Prob $> F$ (H_0: $\gamma_s = -1$)	0.934	0.109	0.351	0.873
No. obs.	176	2254	409	1538
No. countries for Std. Err. clustering	15	26	17	23
Prob $> F$ (H_0: joint insignificance of parameters)	0.016	0.000	0.000	0.031
Root MSE	0.365	0.097	0.379	0.379

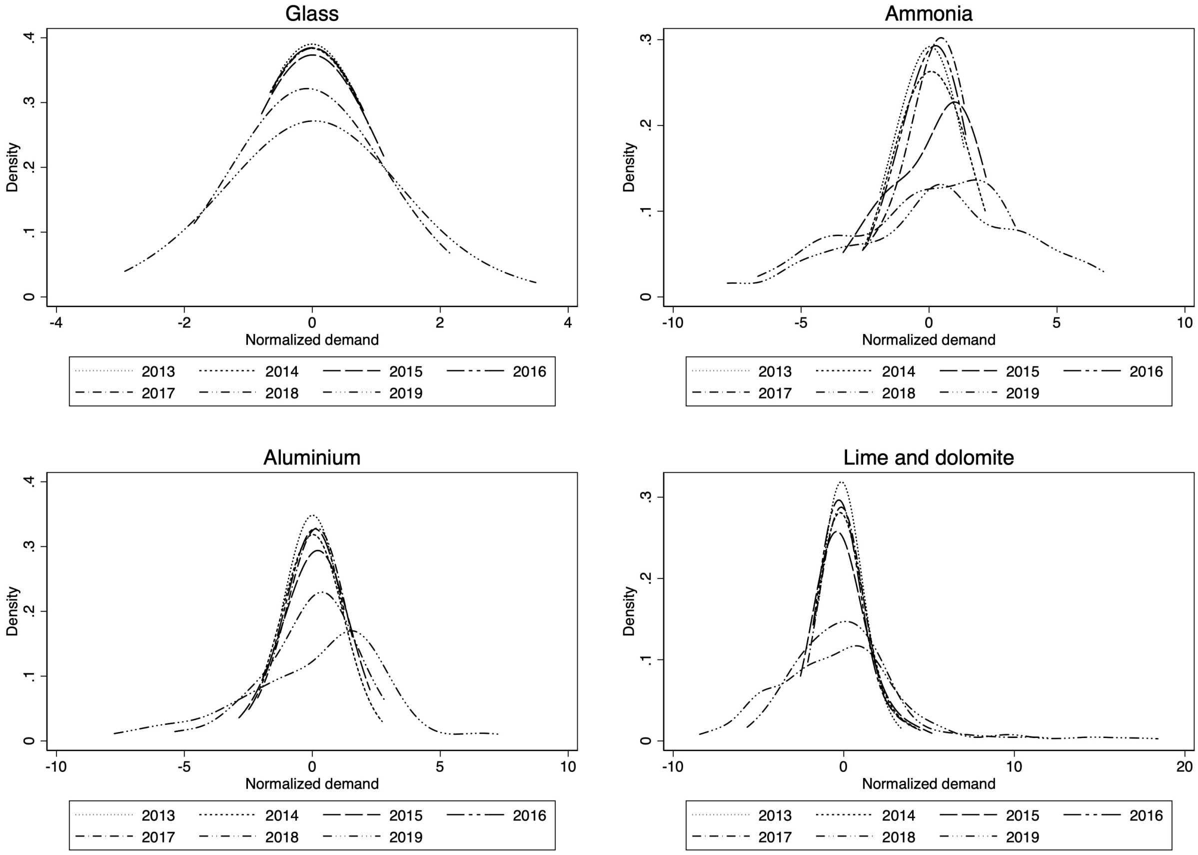
Notes: Estimation by OLS of equation (11), sector-by-sector over 2013-2019. Standard errors in parentheses are clustered at the country level. *** p<0.01, ** p<0.05, * p<0.1.

Table 2: Variance decomposition of compliance costs deviations.

	[1] Ammonia	[2] Glass	[3] Aluminium	[4] Lime and dolomite	[5] Pooled sample
(A): total variance (%)	100	100	100	100	100
(B): total variance purged from country effects	76.232	90.901	89.443	78.816	92.294
(C): total variance purged from time effects	98.590	99.853	99.773	99.976	99.966
(D): total variance purged from country and time effects	74.931	90.759	89.217	78.750	92.249
(E): total variance purged from country, time and country-time effects	52.706	84.673	79.130	67.581	88.615

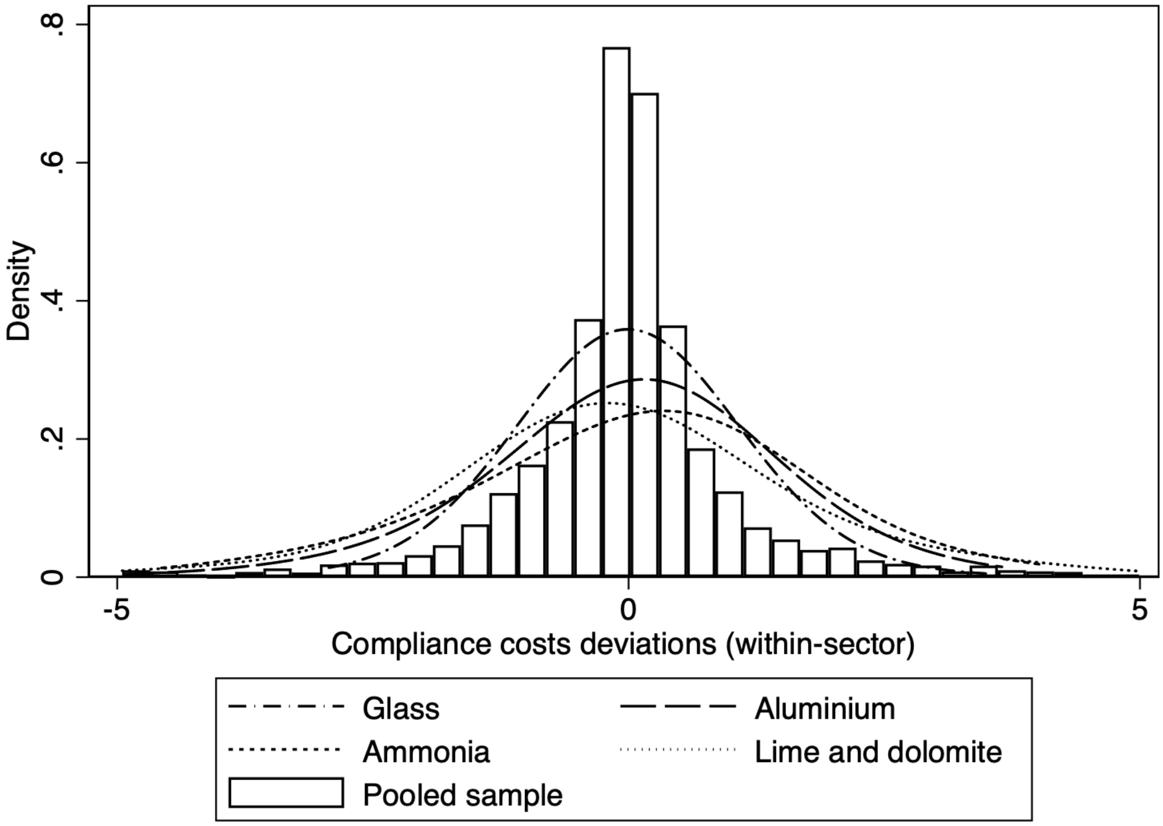
Notes: Total variance (A) is the total variance of Δc_{its} normalized to 100. (B), (C), (D) and (E) are obtained as the variance of the regression residuals resulting from regressing Δc_{its} on country effects, time effects, country and time effects, and country, time and country-time effects, respectively, expressed as a % of (A).

Figure 1: Within-sector distribution of the normalized demand of allowances, by year of Phase 3.



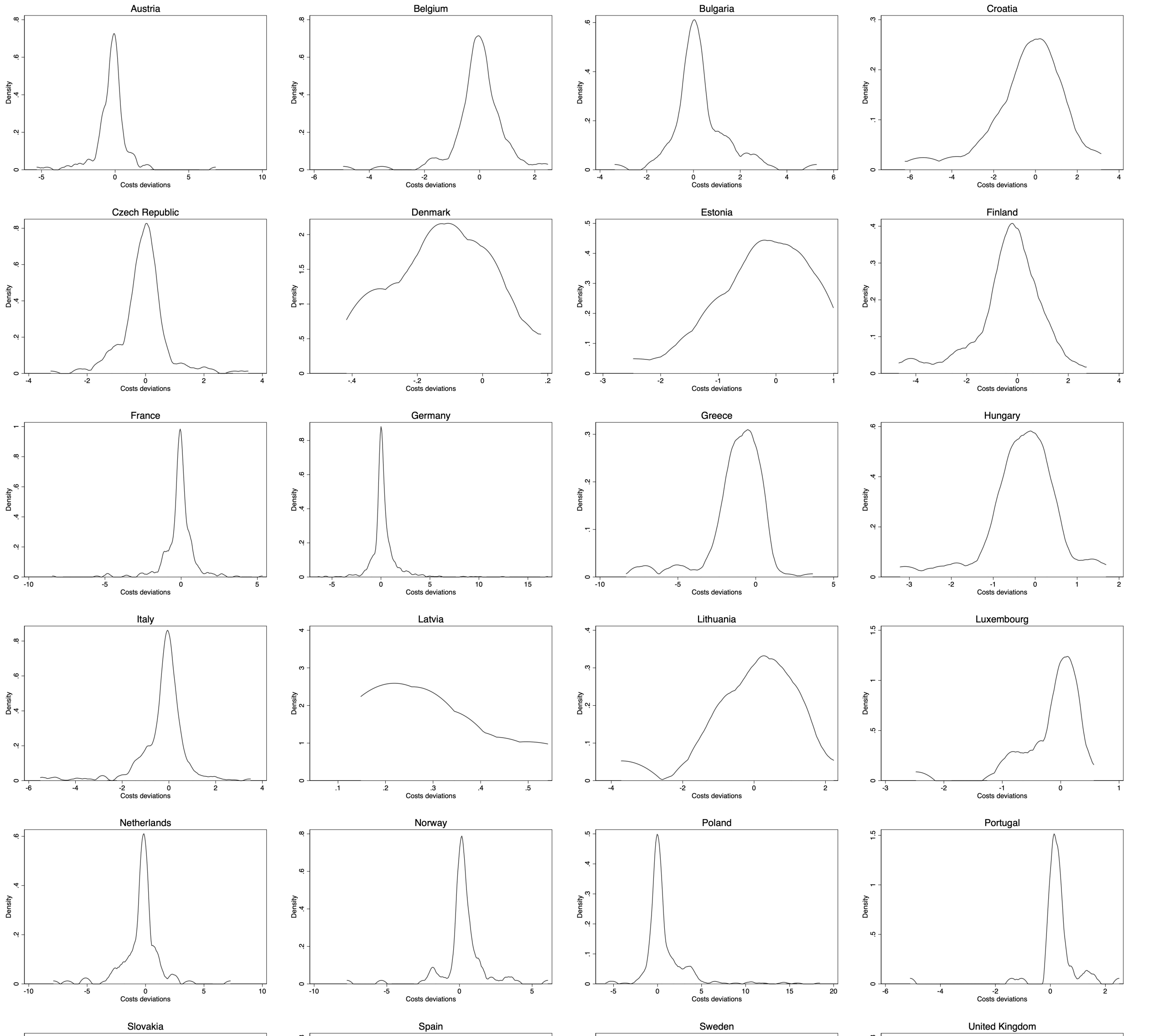
Notes: The normalized demand of allowances d_{its} is measured at the installation-level as in (7).

Figure 2: Compliance costs deviations: within-sector distributions.



Notes: Distributions of the compliance costs deviations Δc_{its} obtained as the difference between installation i's normalized compliance cost and the sector average as in (14). The histogram gives the actual distribution of Δc_{its} for the pooled sample (all sectors). The overlaying lines represent the normal density functions of Δc_{its} for each sector.

Figure 3: Compliance costs deviations: within-sector distributions by country.



Notes: Country distributions of compliance costs deviations Δc_{its} obtained as the difference between installation i's normalized compliance cost and the sector average as in (14).