Clean Technical Change and Factor Substitution under Carbon Pricing

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Introduction

The European Union Emissions Trading System (EU ETS), established in 2005, is the largest carbon pricing scheme in history. In the first 15 years of the program, emissions from regulated stationary sources have fallen by more than 30%. Understanding the mechanisms behind these reductions is critical for assessing the effectiveness of carbon pricing and informing future policy design. This paper examines how firms have adjusted their production and input choices under the EU ETS, the extent to which clean technical change has lowered the cost of emissions reductions, and the broader implications of carbon pricing for employment, capital investment, and productivity.

Our first contribution is methodological. We introduce a novel approach for estimating firms' abatement cost functions by leveraging insights from the productivity literature. Specifically, we show how to identify key parameters of the abatement function by estimating the elasticity of substitution between emissions and labor, applying standard econometric techniques from the production function estimation literature. We believe this approach offers a valuable framework for studying firm-level abatement behavior under emissions regulation more broadly.

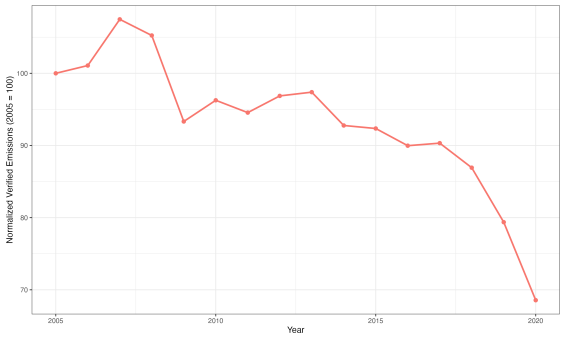
Beyond this methodological contribution, we will provide new empirical evidence on the mechanisms driving emissions reductions under the EU ETS. Namely, we will use our theoretical framework to empirically quantify the relative importance of factor substitution, clean technical change, and market reallocation in explaining observed declines in emissions. This distinction is crucial for evaluating the long-run effectiveness of carbon pricing, as reductions achieved through clean technical change may be more sustainable than those driven by temporary input substitutions. Finally, we will investigate the labor market impacts of emissions pricing, assessing whether emissions reductions have been accompanied by significant employment losses or whether firms have adapted by shifting toward cleaner production technologies.

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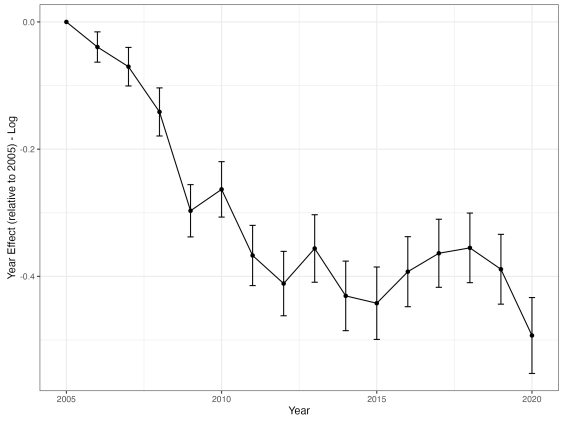
Data

We build a new dataset combining Moody's (previously Bureau van Dijk) Orbis financials with firm-level EU ETS compliance data. This merged dataset includes panel information on revenues, labor costs, employment, capital, and verified emissions from over 5,000 firms spanning from 2005 to 2020. Importantly, these data allow us to infer factor prices such as wages and permit prices faced by each firm in each year. Our sample covers more than 60% of regulated emissions. An advantage of these data is that we can track firm performance across many different sectors and over an extended time period.

Figure 1 presents emissions under the EU ETS. In particular, Panel (a) displays the time series of normalized verified emissions, using 2005 as the baseline year. Emissions rise slightly before peaking around 2007, then decline sharply by nearly 40% from 2007 to 2020. However, this figure does not account for the expansion of regulated sectors over the sample period. As a result, part of the observed emissions trend reflects changes in coverage rather than only reductions within firms initially subject to regulation.



(a) Aggregate EU ETS Emissions (Normalized)



(b) Average Within-Firm Emissions Reductions (Logs)

Figure 1: Emissions Trends in the EU ETS

In Panel (b), we estimate within-firm emissions reductions by regressing logged firm emissions on firm and year fixed effects. The plotted coefficients represent the estimated year effects. The results show a steady decline in emissions at the firm level, with estimated reductions of approximately 40% by 2020 relative to 2005. These results indicate that a substantial share of emissions reductions are likely explained by firm-level abatement in contrast to reallocation of production from dirtier to cleaner firms.

Figure 2 extends this analysis by decomposing within-firm emissions reductions across different industries. While most sectors exhibit declining emissions over time, there is considerable heterogeneity. Manufacturing (NAICS 31-33) shows persistent reductions, with emissions falling by approximately 30–50% by the end of the sample period. The utilities sector experiences an even steeper drop, consistent with fuel switching and investments in

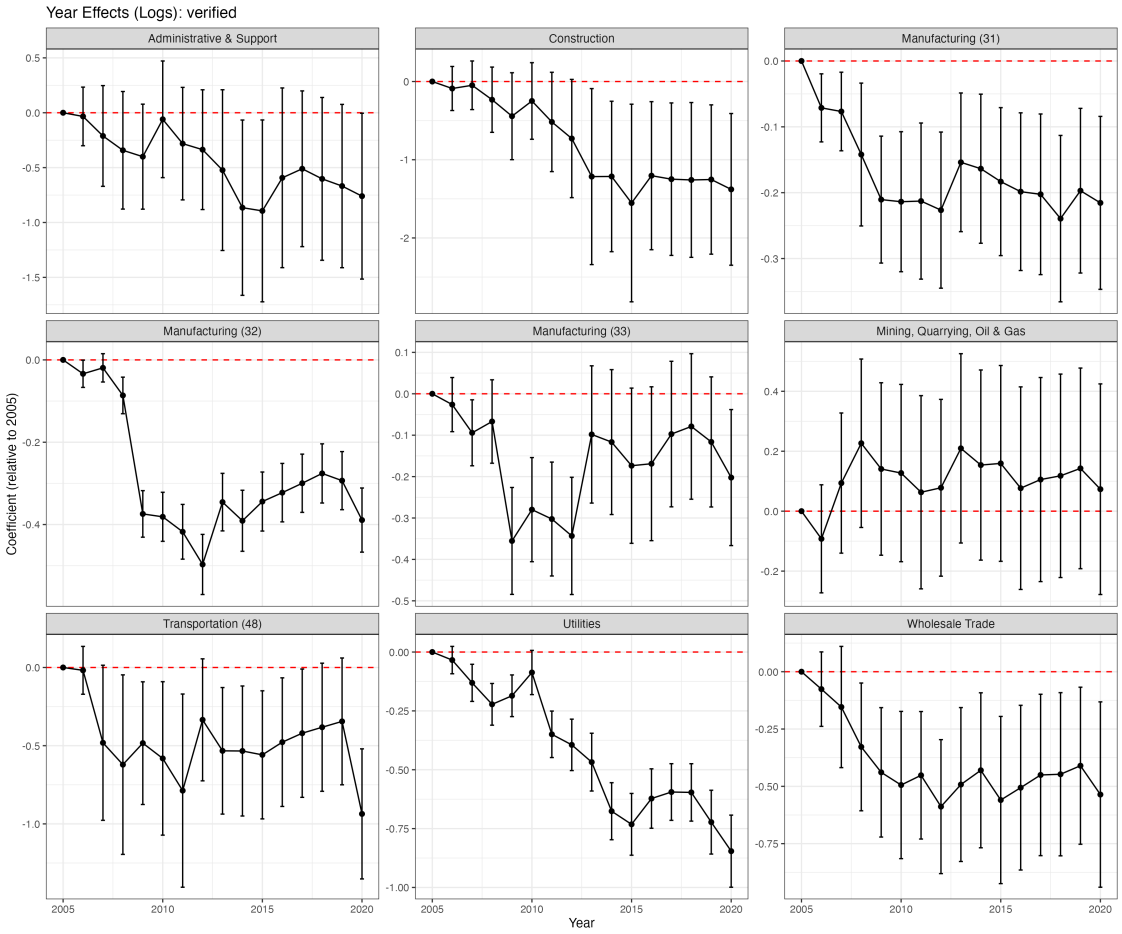


Figure 2: Within Firm Emissions Reductions by Sector (Logs)

renewable energy sources. In contrast, emissions reductions in mining, quarrying, and oil & gas are more volatile, potentially reflecting fluctuating production levels and commodity price cycles.

These trends motivate our research questions on how firms adjust production and input choices under carbon pricing and the role of clean technical change. The observed within-firm emissions reductions suggest that firms are adapting over time, but the heterogeneity across sectors raises important questions about the mechanisms driving these adjustments. Are firms reducing emissions through factor substitution, investments in cleaner technologies, or a decline in production? The sectoral differences further highlight the importance of understanding whether certain industries face higher abatement costs.

1 Theoretical Framework

We begin by modeling firm production decisions where firms explicitly choose their abatement effort. We then demonstrate that this setup is equivalent to a model where firms treat emissions as an input alongside capital and labor, following the approach in Copeland and Taylor (2003). This transformation allows us to leverage familiar empirical strategies from the production function literature, such as estimating the elasticity of substitution. Since these frameworks are equivalent, we can obtain structural estimates of the abatement function.

Production and Abatement Decision: Firms produce output using capital (k) and labor (l) according to a constant elasticity of substitution (CES) function:

$$F(k,l) = Af(k,l) = A\left[\alpha k^{\rho_0} + (1-\alpha)l^{\rho_0}\right]^{\frac{1}{\rho_0}}, \tag{1}$$

where A is a Hicks-neutral productivity term, α governs the relative importance of capital, and ρ_0 determines the elasticity of substitution between capital and labor ($\sigma_0 = 1/(1-\rho_0)$).

Firms allocate a fraction $(1-\theta)$ of resources to production and θ to abatement. The firm's effective output thus depends on the fraction of resources allocated to production:

$$y = (1-\theta)F(k,l). \tag{2}$$

Emissions are proportional to output but reduced by the abatement function $\psi(\theta)$:

$$e = \psi(\theta)F(k,l), \tag{3}$$

where $\psi(\theta)$ captures the emissions reduction from abatement. In Appendix A, we show that the functional form for abatement: $\psi(\theta;\delta,\rho,A,B) = \frac{1}{AB}\left(\frac{\delta-1+(1-\theta)^{\rho}}{\delta}\right)^{\frac{1}{\rho}}$ is equivalent model where firms choose emissions as a direct input in production.[1] Specifically, the firm's total output can be rewritten as a CES function of productive resources ($f(k,l) = \frac{F(k,l)}{A}$) and emissions ($e$):

$$y = A\left[(1-\delta)f(k,l)^{\rho} + \delta(Be)^{\rho}\right]^{\frac{1}{\rho}}. \tag{4}$$

For convenience, we will impose an addition restriction that $\rho_0 = \rho$ (we plan to relax this), then the resulting production function has the following familiar form:

[1] This functional form is chosen for empirical convenience, but similar equivalence should hold for more general functional forms. Noteably, this form ensures that emissions decline as abatement effort θ increases, while allowing for varying degrees of substitutability between abatement and output.

$$y = A\left[\alpha_k k^\rho + \alpha_L l^\rho + (1 - \alpha_K - \alpha_L)(Be)^\rho\right]^{\frac{1}{\rho}}. \tag{5}$$

Since these frameworks are observationally identical, we can estimate the elasticity of substitution and abatement parameters using standard empirical techniques from the production function literature to estimate the model parameters.

Importantly, the term, B, captures firm-level differences in abatement technology. Conceptually, B captures emissions-biased technical change. In traditional CES production functions, Hicks-neutral productivity A scales overall output efficiency without changing input proportions. By contrast, B specifically governs the efficiency with which firms use emissions, akin to labor- or capital-augmenting technical change in standard growth models. A increase in B over time suggests that firms have increasing access to cleaner production methods.

The model, therefore, allows us to decompose each firm's emission reductions into two components: (1) factor substitution, where firms adjust their input mix in response to changes in emissions prices, (2) clean technical change: where firms reduce emissions at a given level of output. In our empirical analysis, we estimate the average evolution of B to assess the relative importance of these mechanisms in emissions reductions under carbon pricing. This approach allows us to quantify the contribution of clean technical change to firm-level abatement and evaluate how firms respond to changes in emissions permit prices over time.

2 Empirical Strategy

Our empirical analysis estimates the elasticity of substitution between emissions and labor using cost-share equations derived from the firm's first-order conditions. We focus on labor-emission substitution because we observe substantial cross-sectional variation in wages across firms, while capital costs are not directly available at the firm level and primarily vary at the aggregate level. By leveraging variation in labor costs, we can estimate the degree to which firms adjust their emissions in response to changes in relative input prices.

Let w_{jt} denote the wage rate paid by firm j in year t, and let π_t denote the emissions permit price in year t, which varies only at the aggregate level. The firm's optimal input allocation satisfies the condition:

$$\frac{w_{jt} l_{jt}}{\pi_t e_{jt}} = B_{jt}^{1-\sigma} \left(\frac{w_{jt}}{\pi_t}\right)^{1-\sigma} \left(\frac{\alpha_L}{1 - \alpha_L - \alpha_K}\right)^{\sigma}, \tag{6}$$

where σ is the elasticity of substitution between emissions and labor. Taking logarithms, we obtain the estimating equation:

$$\ln\left(\frac{w_{jt}l_{jt}}{\pi_t e_{jt}}\right) = (1-\sigma)\ln(B_{jt}) + (1-\sigma)\ln\left(\frac{w_{jt}}{\pi_t}\right) + \sigma\ln\left(\frac{\alpha_L}{1-\alpha_L-\alpha_K}\right) + \varepsilon_{jt}. \quad (7)$$

Defining $f_{jt} = \frac{w_{jt}l_{jt}}{\pi_t e_{jt}}$ as the labor-emission cost share ratio for firm j in year t, we estimate σ using the regression:

$$\ln(f_{jt}) = \beta_0 + \beta_1 \ln\left(\frac{w_{jt}}{\pi_t}\right) + \varepsilon_{jt}, \quad (8)$$

where $\sigma = 1 - \beta_1$.

A key identifying assumption is that the relative price of labor to emissions permits, $\frac{w_{jt}}{\pi_t}$, is exogenous to firm-level unobserved factors affecting emissions and labor choices. However, two potential sources of bias must be addressed. First, emissions permit prices π_t vary over time, and improvements in abatement technologies may be correlated with these price changes, leading to an upward bias in β_1. Second, firm-level unobservables, such as sector-specific regulatory constraints or emissions abatement investments, may be correlated with observed wages.

To mitigate these concerns, we incorporate exogenous clean technical changes into our empirical framework. In particular, we assume that clean technical change follows an exponential growth process:

$$B_{jt} = \exp(B_0 + \gamma t + \eta_{jt}), \quad (9)$$

where B_{jt} represents firm-specific clean technology, B_0 is an initial baseline level, γ is the rate of technical progress, and η_{jt} captures firm-level deviations from the trend. Substituting this into Equation (7), we obtain:

$$\ln(f_{jt}) = \beta_0 + \beta_1 \ln\left(\frac{w_{jt}}{\pi_t}\right) + \beta_2 t + \varepsilon_{jt}, \quad (10)$$

where $\beta_2 = \gamma$ identifies the trend in emissions-saving technology. A positive estimate of β_2 would indicate that firms, on average, reduce emissions intensity over time, even after controlling for changes in relative input prices.

Alternatively, if clean technical change does not follow a smooth time trend, we can replace the linear trend with a set of time fixed effects:

$$\ln(f_{jt}) = \beta_1 \ln\left(\frac{w_{jt}}{\pi_t}\right) + \lambda_t + \eta_{jt}. \quad (11)$$

Here, λ_t captures arbitrary changes in abatement technologies over time, allowing for non-linear improvements in emissions efficiency. This specification provides a more flexible way to account for policy-driven or sector-specific technological shifts that may not follow a smooth trend.

While controlling for time variation helps mitigate omitted variable bias, wages may still be endogenous to firms' emissions choices. To address this, we plan to implement an instrumental variables (IV) strategy, following Raval (2019), using industry-region-specific labor demand shocks as instruments for wages.

Very Preliminary Results

Our preliminary estimates reveal several findings:

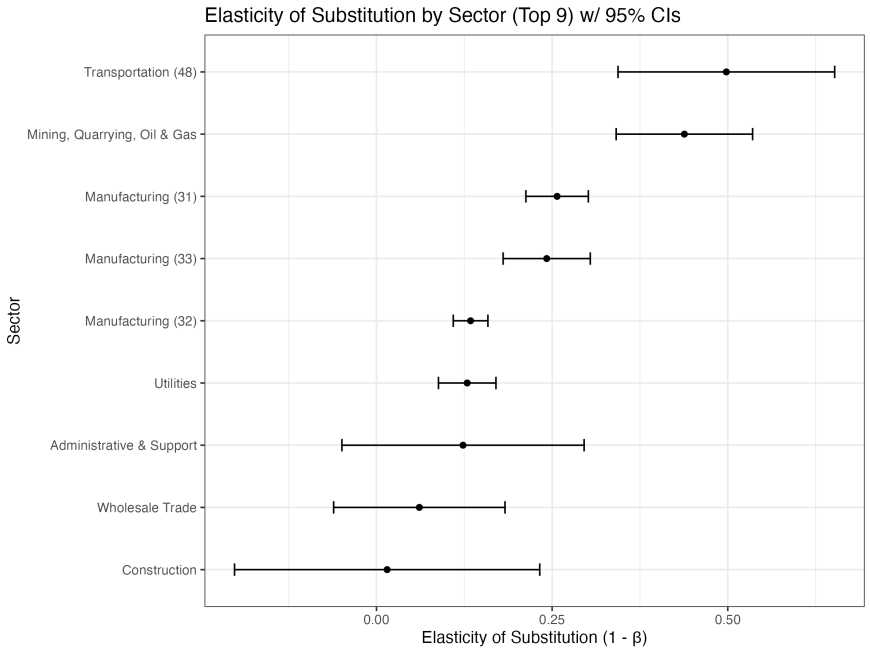


Figure 3: Elasticity of Substitution by Sector (Top 9) with 95% Confidence Intervals

1. **Elasticity of Substitution:** The elasticity of substitution (σ) between emissions and labor is low, ranging from 0.14 to 0.28 across specifications. This indicates that emissions and labor are gross complements, limiting substitution potential in the short run.

    - The elasticity of substitution varies substantially across industries. As shown in Figure 3, the transportation sector exhibits the highest elasticity of substitution,

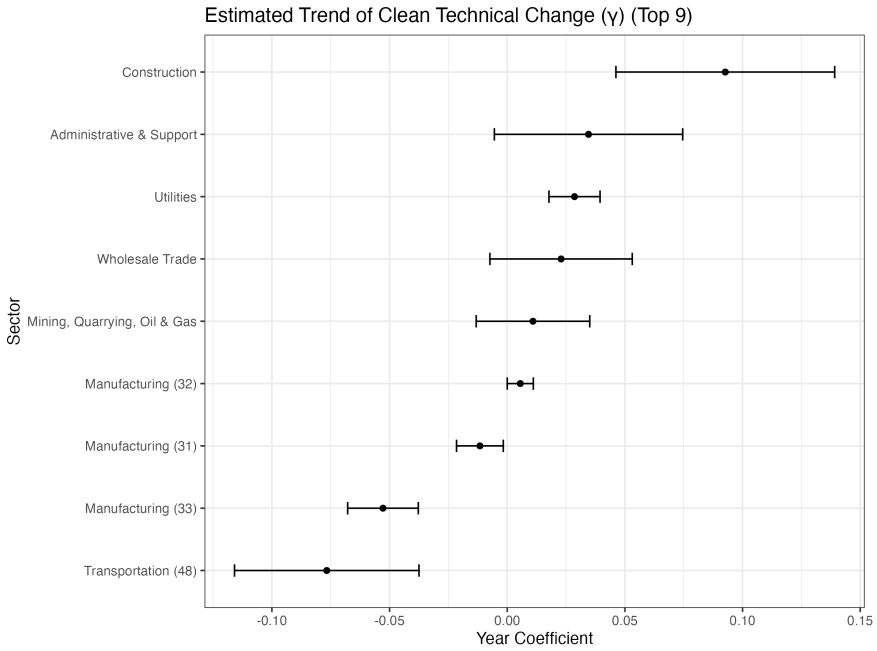


Figure 4: Estimated Trend of Clean Technical Change (γ) by Sector (Top 9)

with an estimate close to 0.50. This suggests that firms in this sector can more easily adjust their input mix.

- In contrast, the mining, quarrying, and oil & gas sector has one of the lowest estimated elasticities, reflecting the difficulty of reducing emissions in industries heavily reliant on fossil fuel extraction and processing. Similarly, the utilities and manufacturing sectors (NAICS 31-33) show low substitution elasticities, indicating that emissions reductions in these sectors through factor reallocation in the short-run is very limited.

2. **Clean Technical Change:** The rate of clean technical change (γ) is approximately 2% per year, suggesting substantial efficiency gains over time that mitigate the adverse impact of carbon pricing on firms in regulated sectors.

   - The evolution of clean technical change varies substantially across industries. As shown in Figure 4, construction exhibits the most significant positive trend, although the estimate is noisy.
   - Utilities also show a meaningful positive trends in clean technical change parameter, possibly due to falling cost of renewable energy over time.
   - Conversely, transportation and manufacturing (NAICS 31-33) show negative or near-zero trends, suggesting that firms in these industries have seen limited technological progress in emissions reductions. Note that only airlines are regulated under EU ETS, not vehicles. We will continue to investigate these results as they are very preliminary.

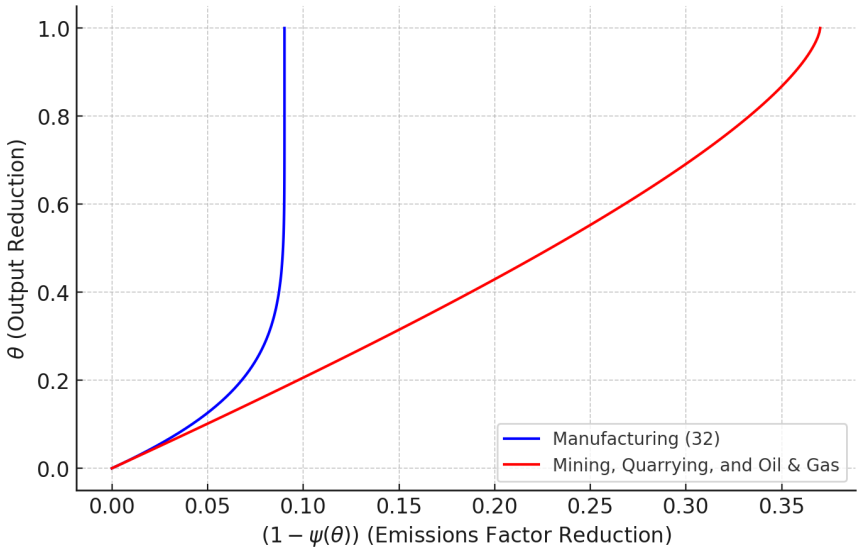


Figure 5: Abatement Functions

- The mining, quarrying, and oil & gas sector shows almost no trend in clean technical change.
- **Abatement Functions:** The elasticity of substitution (σ) determines how easily firms can substitute emissions with other inputs, shaping the abatement function for each industry. Figure 5 plots the average abatement function for firms in two selected industries. The x-axis of the graph represents $(1 - \psi(\theta))$, which corresponds to the emissions factor reduction. This measures the proportion by which emissions intensity decreases due to abatement efforts. A value close to zero indicates minimal emissions reduction, whereas higher values signify more aggressive emissions abatement. The y-axis represents θ, which corresponds to output reduction. This captures the extent to which firms reduce their production levels as a consequence of abatement efforts. A value of zero means no reduction in output, while higher values indicate increasing reductions in production due to efforts to cut emissions.

  The shape of the curves reflects the relationship between emissions reduction and output loss. The steep curvature of the manufacturing (blue) curve suggests that even small reductions in emissions require significant output reductions, due to the low elasticity of substitution between emissions and other inputs. In contrast, the mining, quarrying, and oil & gas sector (red) follows a more gradual trajectory, indicating that emissions reductions can be achieved with relatively lower output losses, implied by a higher elasticity of substitution.

Concluding Thoughts

This paper is a work in progress. This spring we will focus on refining the empirical model and ensuring robustness across different specifications. We aim to explore industry-specific dynamics in greater depth and assess the role of heterogeneity in clean technical change across firms. Additionally, we will address potential endogeneity concerns more rigorously, particularly those related to the interaction between emissions prices and unobserved technological shocks. One of our next steps is to empirically decompose the observed emission reductions into within-firm adjustments (e.g., substituting inputs, adopting cleaner technologies, or improving operational efficiency) to across-firm reallocation of production from dirty to clean firms. Ultimately, we aim to contribute by quantifying the efficiency of a major carbon pricing scheme and providing new insights into carbon pricing's implications for workers in regulated sectors, capital investment decisions, and firm productivity.

References

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A Equivalence of Abatement and Emissions-as-Input Frameworks

This appendix proves that a firm maximizing output while allocating resources between production and abatement, as modeled in Section 2, is equivalent to a firm choosing emissions as an input in production.

Recall, $F(k,l) = A\left[\alpha k^{\rho_0} + (1-\alpha)l^{\rho_0}\right]^{\frac{1}{\rho_0}}$, for convenience, define $f(k,l) = \frac{F(k,l)}{A}$ as production net of the TFP term. Then emissions are given by:

$$e = \psi(\theta) A f(k,l). \tag{12}$$

Substituting the abatement function $\psi(\theta;\delta,\rho,A,B)$:

$$e = \frac{1}{B}\left(\frac{\delta - 1 + (1-\theta)^{\rho}}{\delta}\right)^{\frac{1}{\rho}} f(k,l). \tag{13}$$

Raising both sides to the power ρ:

$$e^{\rho} = \frac{1}{B^{\rho}} \left(\frac{(\delta - 1) f(k,l)^{\rho} + ((1-\theta) f(k,l))^{\rho}}{\delta} \right). \tag{14}$$

From Equation (2), net output is:

$$y = (1-\theta) A f(k,l). \tag{15}$$

Rewriting in terms of emissions:

$$y = A f(k,l) - A\theta f(k,l). \tag{16}$$

Solving for θ:

$$\theta = 1 - \frac{y}{A f(k,l)}. \tag{17}$$

Substituting into the emissions equation:

$$e^{\rho} = \frac{1}{B^{\rho}} \left(\frac{(\delta - 1) f(k,l)^{\rho} + \left(\frac{y}{A}\right)^{\rho}}{\delta} \right). \tag{18}$$

Rearranging terms:

$$\delta e^{\rho} = (\delta - 1) f(k,l)^{\rho} + \left(\frac{y}{A}\right)^{\rho}. \tag{19}$$

Multiplying by A^{ρ}:

$$\delta (Ae)^{\rho} = (\delta - 1) A^{\rho} f(k,l)^{\rho} + A^{\rho} y^{\rho}. \tag{20}$$

Dividing by A^{ρ}:

$$y^{\rho} = A^{\rho} [(1-\delta) f(k,l)^{\rho} + \delta (Be)^{\rho}]. \tag{21}$$

Taking the $\frac{1}{\rho}$ power on both sides:

$$y = A\left[(1-\delta)f(k,l)^{\rho} + \delta(Be)^{\rho}\right]^{\frac{1}{\rho}}. \tag{22}$$