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Complementarity between labor and energy: A firm-level analysis☆

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ABSTRACT

This paper extends the literature on the potential negative employment effects of environmental policy by bringing to the fore a key factor that directly regulates its magnitude: the elasticity of substitution between labor and energy. Using firm-level data from the French manufacturing sector and addressing endogeneity concerns, we provide empirical estimates that point to strong complementarity between labor and energy. We then investigate the empirical relevance of the elasticity of substitution in studying firms' response to changing energy prices. Our findings suggest that the negative employment effects of rising energy prices are largely driven by firms with limited substitution capacity.

1. Introduction

How to limit global warming is one of the most challenging policy questions facing the world today. As the consensus on the impact of human activities on the climate system grows, the need to substantially reduce anthropogenic greenhouse gas emissions is strongly recognized (IPCC, 2014). Among a set of policy instruments designed to facilitate large-scale emissions abatement, market-based regulations such as carbon taxes and emissions trading schemes are gaining popularity around the world. For instance, OECD (2016) compiles effective carbon rates in 41 countries that account for 80% of global energy use and of CO2 emissions and reports that emissions trading schemes are in operation in 30 out of the 41 countries.

Yet, there has also been a strong opposition to such market-based policy instruments that increase energy prices by design and subsequently raise production costs in industries, which may negatively affect employment. Prior studies have investigated the so-called 'job-killing' effects of such regulation in different contexts and provided mixed empirical results. Kahn and Mansur (2013), Marin and Vona (2021) and Dussaux (2020) find a negative relationship between energy prices and employment in manufacturing industries. On the other hand, Martin et al. (2014) and Hille and Möbius (2019) find that such policy measures lead to a reduction in energy consumption and emissions without significant negative effects on labor demand in manufacturing firms.

The current state of the literature therefore requires a deeper understanding of the mechanisms through which firms respond to environmental policies that lead to changes in energy prices. In this paper, we contribute to the debate by bringing to the fore a key factor that directly regulates the effect of energy prices on economic activities and in particular labor demand: the elasticity of substitution between labor and energy. Despite the importance, there is a dearth of empirical evidence on the degree of substitutability between the two production inputs faced by firms and how it affects their capacity to respond to changing regulatory environment. This is what we aim to provide in this paper.

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Our theoretical model that will guide the empirical analysis clearly reveals the two opposing effects behind the net impact of energy prices on labor demand. The first is the output effect whereby higher input prices lower production which leads to lower demand for labor. The second effect is the substitution effect that may lead to higher demand for labor depending on the degree of substitutability between labor and energy faced by firms. Firms with strong input substitution capacity are likely to substitute labor for energy in response to higher energy prices. In this case, the negative output effect would be less pronounced among these firms. This suggests the crucial role of the elasticity of substitution between labor and energy in adjusting the net impact of energy prices on employment.

To empirically probe the workings of the elasticity of substitution between labor and energy, we use firm-level data from the French manufacturing sector for 1994–2015. Understanding how manufacturing firms respond to changing energy prices is of importance given that it takes over 20 percent of the total energy consumption in France (Eurostat, 2018). Furthermore, the data provides rich variation in energy consumption and expenditure at the firm level that allows us to identify the impact of energy prices on labor and energy demand and how it relates to the degree of input substitutability.

Our empirical analysis proceeds in two steps. In the first part, we estimate the elasticity of substitution between labor and energy in order to have a sense of the degree of input substitutability faced by firms. Existing estimates are mostly based on macro level data or without strong attention to endogeneity concerns (e.g., Berndt and Wood, 1975; Koetse et al., 2008). Adding to the literature, we aim to provide rigorous micro estimates of this key parameter by using instrumental variables that address the endogeneity concerns of firm-level energy prices and wages.

In the second part of the analysis, we investigate the empirical relevance of the elasticity of substitution in studying firms' response to changes in energy prices. To this end, we examine the effect of energy prices on labor and energy demand and study if the elasticity of substitution between labor and energy regulates these effects in ways that are theoretically consistent. Since our goal is to explicitly account for the importance of the elasticity of substitution, we construct a firm-level measure of substitution elasticity that allows us to distinguish firms according to their flexibility in input substitution. The measure is constructed by the percentage change in relative quantities of energy and labor due to a percentage change in their relative prices according to the definition of the elasticity.

We report three main empirical findings. First, labor and energy tend to be complements in most firms with the estimated elasticity of substitution between labor and energy of around 0.6. Although we observe a fair amount of heterogeneity across industries, a majority of industries (17 out of 19) have estimates of the elasticity of substitution below unity. Second, we find evidence for the theoretical prediction that the negative impact of energy prices on labor demand is weaker among firms with higher input substitution capacity than among those with lower input substitution capacity. When energy prices increase, firms with higher input substitution capacity may substitute more expensive energy with labor, which would offset the negative output impact to some extent. This countervailing channel is more constrained among firms with lower degrees of input substitutability. We observe from the data that the overall negative employment effects of rising energy prices are largely driven by these firms. Finally, the opposite is observed with respect to energy consumption. Not surprisingly, high-flexibility firms tend to reduce their energy consumption by a larger margin in response to higher energy prices because they could substitute away from energy more easily than their counterparts with lower input substitutability. This empirical documentation of how the elasticity of substitution regulates the effects of energy prices on firms' economic activities advances our understanding of the mechanisms behind how firms respond to energy prices in a changing regulatory environment.

Our paper relates to several strands of literature. First, our emphasis on arguably the most important factor behind how and why firms adjust labor demand in response to changes in energy prices – the degree of substitutability between the two inputs in production – adds a fresh and yet intuitive angle to the on-going debate regarding the economic costs of environmental regulation (Berman and Bui, 2001; Greenstone, 2002; Walker, 2011; Kahn and Mansur, 2013; Martin et al., 2014, 2016; Marin and Vona, 2021). Our analysis shows that the elasticity of substitution plays an important role in determining the magnitude of the impact of higher energy prices on employment and energy consumption. Notably, we find that the negative employment effects of energy prices are driven by low-flexibility firms. High-flexibility firms, on the other hand, are largely unaffected by rising energy prices.

Second, this paper connects to the empirical literature examining the elasticity of substitution in the energy context (see Haller and Hyland, 2014, for a review of this literature and references therein). The literature emerged as a response to the oil crisis in the 1970s and the subsequent growth in the availability and performance of energy-saving technologies, thus mostly focusing on the capital-energy substitutability. Our goal is to extend the literature by studying the degree of substitutability between *labor* and energy faced by firms which directly regulates their response to changing energy prices in terms of labor demand. We find that labor and energy tend to be strong complements in most firms with the estimates of the elasticity of substitution substantially below one.

Last but not least, our results on the substitution process at the firm level contribute to the models exploring long-run macroeconomic effects of rising energy prices, which can be attributed to increasing scarcities or environmental policies. While a first wave of literature found a detrimental effect of poor input substitution on long-run development under such conditions (e.g., Dasgupta and Heal, 1974), multisector models applying endogenous growth theory (Bretschger, 1998; Bretschger and Smulders, 2012) allow to derive the impact of labor-energy substitution on sectoral change which may benefit innovation and growth under realistic conditions. Our empirical results add to a better understanding of the adaptation to higher energy prices with firms and sectors producing different types of output.

The article is organized as follows. Section 2 presents the theoretical model and Section 3 describes the data. Section 4 presents the estimation of the elasticity of substitution between labor and energy. Section 5 examines the impact of energy prices on labor and energy demand and Section 6 concludes.

2. Theoretical model

The theoretical model reflects the dynamic environment in which modern firms are operating; besides manufacturing, innovative activities are key and the main input in research is labor. The other important production input is energy, the focus of our study. We treat labor and energy as static (or 'variable') inputs as in Doraszelski and Jaumandreu (2018) and Levinsohn and Petrin (2003) that are chosen each period to maximize profits; the firm is a price taker in input markets. Capital stock is introduced in the form of knowledge capital.

We consider an economy populated by N firms, each producing a differentiated consumer good Y_i. Aggregate consumption of households C is given by:

$$C = \left[\int_{i=0}^{N} Y_i^{\frac{\eta-1}{\eta}} di \right]^{\frac{\eta}{\eta-1}} \tag{1}$$

where N is the mass of differentiated goods and $\eta \geq 0$ is the elasticity of substitution between two goods; time subscripts are omitted whenever there is no ambiguity. A single firm is assumed to be small compared to the whole market, i.e., it has no impact on total consumption and the aggregate price level (Chamberlinian large-group case); first order conditions for the utility maximization of households yield for the change of demand for good Y_i with changing goods prices:

$$\hat{Y}_i = -\eta \hat{P}_i \tag{2}$$

where P_i is the price of good i and hats denote percentage changes. Each firm i performs three activities. First, it assembles output Y_i from J_i intermediate goods v_i according to:

$$Y_i = \left[\int_{j=0}^{J_i} v_{ij}^{\frac{\omega_i-1}{\omega_i}} dj \right]^{\frac{\omega_i}{\omega_i-1}} \tag{3}$$

where J_i is the mass of differentiated input goods of firm i and $\omega_i \geq 1$ is the elasticity of substitution between two intermediate inputs of i. Assuming symmetry between intermediates, i.e., identical cost functions for all intermediate goods of firm i, we have $v_{i1} = v_{i2} = v_i$ and can write $Y_i = J_i^{1/(\omega_i-1)} V_i$ with $V_i = J_i v_i$. This reveals the gains from specialization for the firm where output is growing with J_i, given by the term $J_i^{1/(\omega_i-1)} > 0$, when holding total input, V_i, constant. As this stage of production does not require further inputs, the budget for final goods is fully spent for covering the costs of intermediates, i.e., $P_i Y_i = P_{vi} V_i$ where P_{vi} is the price of intermediate goods. In our theoretical model, we could adopt a broader definition of capital so that it would cover physical and knowledge capital. In this case, a new firm would not only need new ideas to enter the market but also new types of machines. With increasing specialization in modern manufacturing this is an intuitive assumption. If the two types of capital were combined to aggregate capital with a Cobb–Douglas function and would exhibit the same cost function when being produced, the current model results are fully preserved.

Second, firm i uses labor N_{Vi} and energy E_{Vi} as inputs to produce intermediate input goods v_i; the aggregate of firm intermediates, V_i, is written as a function of firm input of labor and energy according to:

$$V_i = \left[\lambda_i N_{Vi}^{\frac{\sigma_i-1}{\sigma_i}} + (1-\lambda_i) E_{Vi}^{\frac{\sigma_i-1}{\sigma_i}} \right]^{\frac{\sigma_i}{\sigma_i-1}}, \tag{4}$$

where $\sigma_i \geq 0$ denotes the elasticity of substitution between labor and energy in v-production, λ_i is a firm specific distribution parameter, and N_{Vi} and E_{Vi} denote labor and energy used in intermediates production. Firm i maximizes profits from intermediates production, yielding relative intermediate input quantities and expenditure shares according to:

$$\frac{N_{Vi}}{E_{Vi}} = \left(\frac{\lambda_i}{1-\lambda_i} \right)^{\sigma_i} \left(\frac{W_i}{P_{Ei}} \right)^{-\sigma_i} \tag{5}$$

$$\frac{W_i N_{Vi}}{P_{Ei} E_{Vi}} = \frac{\theta_{NVi}}{\theta_{EVi}} = \left(\frac{\lambda_i}{1-\lambda_i} \right)^{\sigma_i} \left(\frac{W_i}{P_{Ei}} \right)^{1-\sigma_i}, \tag{6}$$

where W_i is the labor wage and P_{Ei} the energy price for firm i. The log of relative input quantities as a function of the elasticity of substitution between the two inputs, used in the empirical part below, is given by:

$$\log\left(\frac{E_{Vi}}{N_{Vi}} \right) = \sigma_i \log\left(\frac{W_i}{P_{Ei}} \right) + \sigma_i \log\left(\frac{\lambda_i}{1-\lambda_i} \right). \tag{7}$$

where the second term on the right-hand side represents a firm-specific determinant of relative input use. This firm heterogeneity is relevant to our empirical analysis and we account for it by including firm fixed effects.

Labor demand for intermediates production of firm i can be written as $N_{Vi} = a_{NVi} V_i$ where a is the well-known Leontief input factor (here for labor input N in the intermediate sector V). The percentage change of labor demand is then given by $\hat{N}_{Vi} = \hat{a}_{NVi} + \hat{V}_i$. Minimizing the costs of the firm yields $\hat{a}_{NVi} = -\theta_{EVi}\sigma_i(\hat{W}_i - \hat{P}_{Ei})$ and using the Wong-Viner Envelope Theorem results in $\hat{V}_i = -\eta\left(\theta_{NVi}\hat{W}_i + \theta_{EVi}\hat{P}_{E,i}\right)$, so that:

$$\hat{N}_{Vi} = -\left[\sigma_i \theta_{EVi} + \eta \theta_{NVi}\right] \hat{W}_i - (\eta - \sigma_i)\theta_{EVi} \hat{P}_{Ei} \tag{8}$$

which shows the impact of input prices on labor demand, featuring the elasticity of substitution σ_i. It becomes evident that the change of labor demand, $\hat{N}_{Vi}$, depends on the effects of energy price changes as well as of wage changes, $\hat{W}_i$. Regarding the latter, we distinguish between fixed and flexible wages, which can be interpreted as a distinction between the short and the longer run. In our data, we observe that wages tend to be sticky without much variation over time; the firm-specific one, three, five, and ten year autocorrelation coefficients for wages after controlling for sector fixed effects are 1.201, 0.905, 0.940, 0.957, respectively. An alternative interpretation is that wages do not change because the firm's employment is small against the rest of the labor market so that the firm has no market power when setting its wages.

Assuming constant wages ($\hat{W}_i = 0$), Eq. (8) can be simplified to:

$$\hat{N}_{Vi} = -(\eta - \sigma_i)\theta_{EVi}\hat{P}_{E,i} \tag{9}$$

which is an equation we will carry to the data below. It reveals that an increase in energy price ($\hat{P}_{Ei} > 0$) has a negative output effect through shrinking goods demand, given by $-\eta\theta_{EVi}$, and a counteracting substitution effect of size $\sigma_i\theta_{EVi}$, which highlights the importance of the elasticity of substitution between labor and energy.

With fixed wages, the impact of energy prices on firm's energy use is calculated from $\hat{E}_{Vi} = \hat{a}_{EVi} + \hat{V}_i$ according to:

$$\hat{E}_{Vi} = -\left[\eta\theta_{EVi} + \sigma_i\theta_{NVi}\right]\hat{P}_{Ei}$$

which is unambiguously negative, dependent on the substitution elasticity, and also tested below. Specifically, the equation shows that energy prices have a separate effect on energy use which is independent of the elasticity and another effect which depends on the elasticity.

At any point of time, the mass of intermediate varieties is given. When we consider the effect of changing prices *and* wages, the percentage change of firm i's output is determined by $\hat{Y}_i = -\eta\hat{P}_i$, i.e.,

$$\hat{Y}_i = -\eta(\theta_{EVi}\hat{P}_{E,i} + \theta_{NVi}\hat{W}_i). \tag{10}$$

The impact of rising energy prices on output is negative when the energy price change is not overcompensated by falling wages, which has to be taken into account when looking at the longer run and for the case where the firm has a flexibility to set its own wages. We evaluate endogenous wages jointly with the research sector, to which we turn now.

As a third activity, each firm i uses (in-house) R&D to create new intermediates goods varieties using labor and energy input, N_{gi} and E_{gi}. We posit proportional spillovers from existing knowledge to the creation of new knowledge at the firm level, i.e., we write $\dot{J}_{ij} = F(N_{gi}, E_{gi})J_{ij}$ where the dot denotes the time derivative and F has the usual properties of a neo-classical production function; F is multiplied by the spillover term J_{ij} because significant learning is one of the main characteristics of the research sector.[1] Then, we have $\dot{J}_{ij}/J_{ij} \equiv g = F(N_{gi}, E_{gi})$ determining innovation growth (see Grossman and Helpman, 1991, p. 58 for further details). Labor demand for research of firm i is written as $N_{gi} = a_{Ngi}g_i$ which reads in percentage changes:

$$\hat{N}_{gi} = \hat{a}_{Ngi} + \hat{g}_i.$$

This says that research labor demand grows with the percentage change of a firm's research activity, $\hat{g}$, and of labor's unit input factor in the research lab, $\hat{a}_{Ngi}$. To include energy prices we note first that it is optimal for the firm to set the "prices" of intermediates in the internal calculation by using a mark-up over marginal costs which is constant and amounts to $\omega_i/(\omega_i - 1)$. This yields a constant share of intermediates' revenues which is exactly used up to cover the costs of new innovations in the optimum. Put differently, it is optimal for the firm to behave in terms of pricing as if the three activities of crafting final goods, intermediates, and new innovations were carried out by different firms selling and buying the goods on free markets. As a consequence, we have $\hat{g}_i = -\hat{P}_{gi}\zeta$ where P_{gi} is the unit cost of a new innovation (patent), i.e., $\hat{P}_{gi} = \theta_{Egi}\hat{P}_{Ei} + \theta_{Ngi}\hat{W}_i$ with the θs denoting the cost shares in research and $\zeta > 1$ a constant (see Grossman and Helpman 1991 p. 141–143). Using this and the procedure of Eq. (8) to calculate $\hat{a}_{Ngi}$ the change of research labor demand becomes:

$$\hat{N}_{gi} = -\left[\sigma_i\theta_{Egi} + \zeta\theta_{Ngi}\right]\hat{W}_i - (\zeta - \sigma_i)\theta_{Egi}\hat{P}_{Ei}. \tag{11}$$

The equation shows that both wage and price changes have an impact on the firm's demand for labor in R&D. The impact of increasing energy prices ($\hat{P}_{Ei} > 0$) is analogous to the case of intermediate goods above; rising energy prices have a negative output effect through shrinking demand for innovation, given by $-\zeta\theta_{Egi}$, and a counteracting substitution effect of size $\sigma_i\theta_{Egi}$, which highlights the importance of the elasticity of substitution between labor and energy also in research activities. We assume σ_i to be firm specific, i.e., to be identical in all firm activities for simplicity. With $\zeta > \sigma_i$ the impact of energy prices on R&D labor is negative. However, increasing input flexibility, i.e., a rising σ_i, reduces the negative impact. With high σ_i, the effect may become neutral or positive, even when wage changes are disregarded. We will explore empirically the direction of the overall effect and test for the separate impact of the substitution elasticity by distinguishing between high- and low-flexibility firms.

To determine wages and energy use, we consider the use of labor and energy jointly on the firm level. Firm employment, N_i, and energy use, E_i, are used for the two activities, research and manufacturing according to:

$$\begin{bmatrix} N_i \\ E_i \end{bmatrix} = \begin{bmatrix} a_{NVi}(W_i, P_{Ei}) \\ a_{EVi}(W_i, P_{Ei}) \end{bmatrix} V_i + \begin{bmatrix} a_{Ngi}(W_i, P_{Ei}) \\ a_{Egi}(W_i, P_{Ei}) \end{bmatrix} g_i. \tag{12}$$

[1] Our assumption on within-firm spillovers are motivated by intensive knowledge exchange between different cohorts of managers and engineers, to include additional spillover types would not change the results derived in this paper.

The equation shows that N_i and E_i are equal to the appropriate Leontief input factors a multiplied by sectoral outputs, V_i and g_i. To calculate the effects of changing energy prices on the percentage changes of the endogenous variables we can proceed as we did when deriving Eqs. (8) and (11). However, two questions arise at this point. First, is labor reallocated within the firm after a change of energy prices or is (some of) it leaving the firm? In the first case, we can set $\hat{N}_i = 0$, while we have $\hat{N}_i < 0$ in the second where the size of the effect depends on determinants such as general labor market conditions and frictions. Second, how do we model energy supply for the firm? Here we assume that energy prices change according to policy and the firms can flexibly adjust their energy use in equilibrium. Then, the two expressions in Eq. (12) can be solved to determine percentage changes of wages and energy use; changes in wages and energy prices then determine the innovation rate following $\hat{g}_i = -\hat{P}_{gi}\zeta$.

As a benchmark we calculate the wage adjustment after energy price changes for $\hat{N}_i = 0 \Longleftrightarrow \hat{N}_{gi} = -\hat{N}_{Vi}$ by combining Eqs. (8) and (11) and solving for $\hat{W}_i$, which amounts to

$$\hat{W}_i = -\frac{(\eta - \sigma_i)\theta_{EVi} + (\zeta - \sigma_i)\theta_{Egi}}{\Omega}\hat{P}_{Ei} \tag{13}$$

$$\text{where } \Omega = \sigma_i\left(\theta_{EVi} + \theta_{Egi}\right) + \eta\theta_{NVi} + \zeta\theta_{Ngi} > 0 \tag{14}$$

From this expression it becomes obvious that wage changes have the same sign as energy price changes provided that the elasticity of substitution, σ_i, is above a certain threshold level, i.e., when $\sigma_i > \eta, \zeta$. In this case, wages rise with energy prices and innovation is more expensive, which reduces innovative activities. However, when input substitution is relatively poor, i.e., when we have $\sigma_i < \eta, \zeta$, wages decrease with rising energy prices which gives room for potentially higher employment in research and higher research output. The wage effect is strong in the innovation sector as innovative activities are labor intensive, i.e., θ_{Ngi} is close to unity. To conclude, high-flexibility firms are likely to experience an increase in research costs when energy prices rise and will thus not become more innovative. Low-flexibility firms, however, will profit from a wage moderation with energy price growth and have thus the potential to become more dynamic, which is a form of induced innovation; labor leaving the intermediates sector will be accommodated by the research sector. Of course, if we assume $\hat{N}_i < 0$, i.e., that part of the labor is leaving the firm, the effect becomes weaker.

To summarize, the theoretical model provides the following three predictions which we bring to the data:

Prediction 1. Firms with stronger input substitution capacity experience lower employment reduction when energy prices rise.

Prediction 2. Firms with stronger input substitution capacity reduce their energy consumption by a larger amount when energy prices rise.

Prediction 3. When wages are sticky, firms with stronger input substitution capacity experience lower or even no reduction in demand for research labor.

3. Data

We use two main datasets for our empirical analysis. First, we use the Fichier approché des résultats d'Esane (FARE) administered by the French National Institute of Statistics and Economic Studies (Insee). It provides information on firm characteristics such as industry, employees, sales, turnover, and operating costs for the universe of the French manufacturing industry.[2] The second dataset is the Enquête sur les Consommations d'Énergie dans l'Industrie (EACEI), also collected by Insee. It covers a representative sample of manufacturing plants with at least 20 employees and provides plant-level information on energy consumption and expenditures by fuel.

For the analysis that follows, we first aggregate the plant-level information from the EACEI to the firm level in order to merge it with the firm-level information from the FARE. In the aggregation, we only keep firm-year pairs for which all plants of a firm were surveyed in the EACEI to ensure that the aggregation of energy use and expenditure is comprehensive at the firm level. The final dataset contains an unbalanced panel of 11,171 manufacturing firms for the period of 1994–2015.

Table 1 provides summary statistics of the key variables used in the analysis. We calculate the unit cost of energy P_E by dividing the total energy expenditure by the total energy consumption measured in tonne of oil equivalent (TOE). Similarly, a measure of wage is constructed by dividing the total salary and wage payment by the number of employees based on the information from the FARE. It is noteworthy that there exists a substantial degree of heterogeneity across firms in most variables including the average unit price of energy. For example, the average energy price of a firm at the 90th percentile is more than twice higher than that of a firm at the 10th percentile. This heterogeneity arises from the differences in the fuel mix and firm-specific fuel prices resulting from quantity discounts (Marin and Vona, 2021). The relative input and price ratios (E/N and W/P_E, respectively) also display a large degree of dispersion across firms. We exploit firm-level variation in these key variables for identification.

4. Substitution between labor and energy

Our theoretical model brings to the surface the role of the elasticity of substitution between labor and energy in determining how firms respond to energy prices in terms of their input choices. We begin the analysis by estimating this key parameter from our data.

[2] The FARE replaced the Fichier de Comptabilité Unifié dans SUSE (FICUS) in 2008.

Table 1
Descriptive statistics.

Variables	Mean	SD	p10	p90
Energy consumption (E)	753.3	1,412	37.69	1,979
Unit price of energy (P_E)	0.664	0.223	0.417	0.919
Total labor (N)	160.7	409.0	27	322
Output	27,668	121,176	2,232	54,454
Value added	9,368	33,816	1,044	18,569
Wage (W)	26.81	51.01	17.38	35.92
E/N	6.750	20.99	0.661	14.91
W/P_E	44.48	91.73	23.57	66.86

Notes: Descriptive statistics based on EACEI and FARE, 1994–2015. Energy consumption is in TOE. Output and value added are in thousands of Euros. Detailed descriptions for other variables are provided in the main text.

4.1. Specification

The elasticity of substitution is identified by bringing the relationship between the relative input quantities and their relative prices in Eq. (7) to the regression framework:

$$\log\left(\frac{E_{it}}{N_{it}}\right) = \beta_0 + \beta_1 \log\left(\frac{W_{it}}{P_{E,it}}\right) + \delta_t + \omega_{s(i)} + \phi_{c(i)} + \xi_i + \epsilon_{it} \tag{15}$$

where E_{it}/N_{it} is the input ratio of energy consumption to total labor of firm i in year t. The main explanatory variable is the firm-specific price ratio $W_{it}/P_{E,it}$ where W_{it} denote wages and $P_{E,it}$ unit prices of energy. The coefficient of interest β_1 captures the elasticity of substitution between labor and energy. The specification also includes δ_t, $\omega_{s(i)}$ and $\phi_{c(i)}$ that control for unobservable year-, industry-, and region-specific shocks, respectively.[3] We also try more demanding specifications with year by industry and year by region fixed effects. Finally, firm fixed effects ξ_i control for time-invariant firm characteristics such as persistent differences in productivity as well as relative input use (captured by λ_i in Eq. (7)). Standard errors are clustered at the firm level.

4.2. Identification

The identifying assumption is that variation in $W_{it}/P_{E,it}$ is orthogonal to ϵ_{it}, once we control for time-invariant unobservables with an extensive set of fixed effects. However, there may exist time-varying unobservables that affect the estimates of the elasticity of substitution such as demand or idiosyncratic productivity shocks. It is plausible that these sources of bias might make the firm-specific relative prices of inputs endogenous to the extent that such shocks affect input choices, which in turn affect the price ratio through quantity discounts. We expect the bias to be generally upward. For example, given a positive efficiency shock in energy use, the energy to labor input ratio would decrease following reduced energy consumption. This is likely to lower the relative price ratio due to a higher unit cost of energy from lower quantity discounts, leading to upward bias in fixed-effects estimates.[4]

We propose one instrument for each element of the input price ratio. First, as an instrument for the firm-level energy prices, we use the shift-share instrument which is the weighted sum of national fuel prices using firm-specific pre-sample fuel shares as weights, which has been used in prior studies (Linn, 2008; Sato et al., 2019; Marin and Vona, 2021; Jo, 2020). Specifically, the instrument is constructed as follows:

$$P_{E,it}^{IV} = \sum_{j=1}^{10} \phi_{i,t=t_0}^{j}\, P_t^j \tag{16}$$

where P_t^j is the national price of fuel j in year t and $\phi_{i,t=t_0}^{j}$ is the pre-sample share of fuel j in firm i' input mix.[5] The first available year 1994 serves as the pre-sample period and consequently, the estimation sample for IV estimation runs from 1995 to 2015.

The shift-share design of the instrument has been recently discussed in Goldsmith-Pinkham et al. (2020) and Borusyak et al. (2018). These studies emphasize exogenous shares and exogenous shocks as requirements for identification. As for exogenous shocks, given that we rely on energy price shocks at the national level, it is unlikely that they are correlated with firm-level omitted variable bias. Regarding firm-specific pre-sample fuel shares, we follow Goldsmith-Pinkham et al. (2020) and assess the plausibility of their exogeneity by exploring the relationship between the initial fuel shares and our dependent variable. Since we fix fuel shares to the pre-sample period, the exogeneity assumption requires firms' input ratio to be unrelated to the *growth* in the input ratio, rather than *level*. In Table OA1 in Online Appendix, we show that the pre-sample fuel shares used to construct the instrument are not correlated with the growth in the input ratio (log E/N) in subsequent years.

[3] We use the 2-digit NCE (Nomenclature of economic activities) classification provided by the EACEI to control for industry fixed effects.

[4] Or, positive demand shocks that lead to an increase in both labor and energy demand may also affect the relative price ratio and lead to upward bias. Presuming energy demand can be more flexibly adjusted than labor demand and the corresponding prices react in similar magnitudes, the input ratio is likely to rise and an increase in the input price ratio is likely to follow due to larger quantity discounts and a lower unit price of energy.

[5] The included fuels are electricity, steam, natural gas, other types of gas, coal, coke, butane and propane, heavy fuel oil, heating oil and other petroleum products.

Table 2
Elasticity of substitution between labor and energy.

	Dependent variable: $\log \frac{E_{it}}{N_{it}}$				
	(1)	(2)	(3)	(4)	(5)
$\log \frac{W_{it}}{P_{E,it}}$	0.804***	0.807***	0.614***	0.624***	0.638***
	(0.019)	(0.019)	(0.072)	(0.070)	(0.077)
Firm FE	✓	✓	✓	✓	✓
Year FE	✓		✓	✓	
Sector FE	✓		✓	✓	
Region FE	✓		✓	✓	✓
Year × Sector FE		✓			✓
Year × Region FE		✓			
Observations	75,734	75,734	62,763	62,763	62,763
First-stage F statistic			1393.73	716.37	561.762

Notes: Estimates from Eq. (15). Column (1) and (2) report fixed effects estimates. Column (3) to (5) report IV-fixed effects estimates. Column (3) uses the instrument for the firm-level energy price component in the price ratio. Column (4) and (5) use instruments for both energy price and wage in the price ratio. Included fixed effects are marked for each column. Standard errors are clustered at the firm level.

To instrument for firm-level wages, we follow Raval (2019) and use the average local wage to instrument for firm-specific wages. Since local wages are largely formed by local employment conditions, it can isolate variation in the firm-specific wages that are independent of time-varying unobservables at the firm level. To calculate the local wage measure, we construct the average of firm-specific wages in the region where the firm operates.

4.3. Results

Table 2 presents our results. Column (1) shows the estimate with firm fixed effects to control for persistent firm characteristics that may be correlated firms' input choices as well as year, sector, region fixed effects without using instruments. The estimate is below one which suggests that the two production inputs, labor and energy, are complements. Controlling for year by sector and year by region fixed effects do not significantly affect the magnitude of the elasticity (column (2)).

Column (3) - (5) show the results from using instruments developed in the previous section that account for time-varying omitted variable bias.[6] In column (3), we only use the weighted sum of national fuel prices $P^{IV}_{E,it}$ (in log) to instrument for the log price ratio. Once instrumented, the estimate falls in magnitude to around 0.6, compared to the fixed effects estimates of 0.8. The revealed upward bias in fixed effects estimates is consistent with our conjecture. In the next columns, we use the local wage measure as an instrument for the wage element of the input price ratio and find that the point estimates remain similar in magnitude.[7]

From the IV estimates which are our preferred estimates, we again observe that labor and energy tend to be complements. Our estimates are qualitatively comparable to the results in Hassler et al. (2021) that document a strong complementarity between energy and a non-energy composite (that includes labor and capital) with the estimated elasticity of substitution close to zero.

Finally, we examine the elasticity of substitution between labor and energy by industry at the two digit level. Fig. 1 graphically reports the estimates and 95 percent confidence intervals for 19 industries from the specification that includes firm and year fixed effects and uses both instruments. Although we observe a fair degree of heterogeneity across industries, 17 out of 19 industries display point estimates of the elasticity of substitution below one, which implies that labor and energy tend to be complements across various production processes.

4.4. Discussion

We have used micro data with more plausibly exogenous variation in input prices to identify the elasticity of substitution between labor and energy. As a result, our estimates are interpreted as micro elasticities of substitution that capture within-firm substitution towards labor (energy) in response to an increase in the energy price (wage rate).

However, it is recognized in the literature that the micro and macro elasticities can be different (Houthakker, 1955). For example, Oberfield and Raval (2021) show that the macro elasticity of substitution combines the micro elasticity of substitution and the elasticity of demand in the capital-labor context. Applying their insight to our labor-energy context suggests that in addition to our micro elasticity of substitution that captures within firm substitution, the macro elasticity also captures the effect of reallocation across firms: in response to higher energy prices, firms that use labor more intensively will gain a relative cost advantage and win market share from energy-intensive firms. This effect will be stronger when demand is more elastic as consumers respond more to changing relative prices. We note that this reallocation effect is not captured by our micro elasticity estimates.

[6] We report Cragg-Donald Wald F statistic for the overall strength of our instruments. Relevant first stage results are reported in Table OA3.

[7] Note that year by region fixed effects cannot be included in column (5) as the local wage instrument varies at the region-year level.

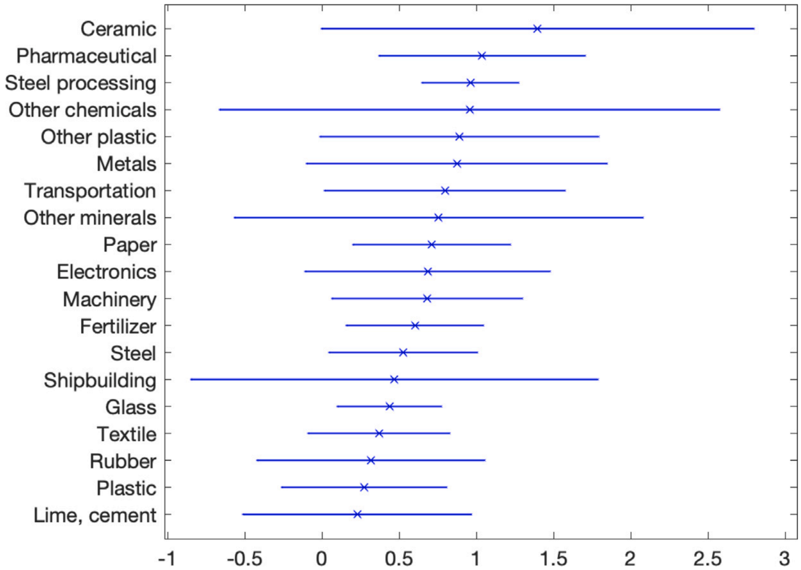

Fig. 1. The elasticity of substitution between labor and energy by industry.
Notes: The figure reports elasticity estimates for each sector with their 95 percent confidence intervals.

5. The impact of energy prices on labor and energy demand

Next, we examine the empirical relevance of the elasticity of substitution between labor and energy in studying firms' response to changes in energy prices and test the predictions from our theoretical model. To this end, we investigate whether the effect of energy prices on labor and energy demand differs across firms associated with different degrees of input substitutability.

5.1. A firm-level measure of input substitutability

The previous section provides estimates of an overall degree of the elasticity of substitution across all firms. However, examining whether firms with different degrees of input substitution capacity respond differently to rising energy prices requires a *firm-level* measure of input substitution. For the purpose, we construct a firm-level measure of the elasticity of substitution between labor and energy from our data. Specifically, the measure is defined by the percentage change in relative quantities of energy and labor divided by the change in their relative prices on an annual basis according to the definition of the elasticity of substitution as in Eq. (7). In the analysis, we use the firm-specific median of this measure of substitutability, σ_i.

Although we believe the measure serves as a suitable proxy for input substitution capacity at the firm level, it is likely to contain bias due to the endogeneity explained in the previous sections. Thus, to check its credibility, we examine how the firm-level measure of input substitutability correlates with other firm characteristics. Table OA2 shows that the measure tends to be negatively correlated with features that reflect the size of a firm such as output, sales and employees, implying that smaller firms tend to be more flexible in their input choices. This observation is consistent with the existing findings that smaller firms are likely to exhibit a higher degree of flexibility than larger firms measured by various indicators including output flexibility (Bartz and Winkler, 2016) and flexibility between fuels (Dussaux, 2020). The mean (median) of the measure is 0.620 (0.596), which falls within the range of the estimates reported in the previous section.

5.2. Does input substitutability matter?

We now examine the first testable prediction from our theoretical model by estimating the impact of energy prices on labor demand with a focus on the degree of substitutability between labor and energy. Our model posits that the effect of energy prices on labor demand can be ambiguous due to the negative output effect and the positive substitution effect. Yet, it is predicted that firms with strong input substitution capacity may reduce employment less than those with limited input substitution capacity (Prediction 1). We estimate the following equation to examine this effect:

$$\log N_{it} = \beta_0 + \beta_1 \log P_{E,it} + \beta_2 \log P_{E,it} * \sigma_i + \xi_i + \rho_{st} + \nu_{ct} + \epsilon_{ijct}, \tag{17}$$

The dependent variable N_{it} measures log employment in firm i in period t. The coefficient β_2 on the interaction term between $P_{E,it}$ and σ_i captures the differential substitution effects across firms with different degrees of input flexibility. The regression also controls for any permanent observed or unobserved firm characteristics with firm fixed effects (ξ_i), annual fluctuations in each

Table 3
The impact of energy prices on labor demand.

	Dependent variable: labor demand				
	All firms			Low-flexibility firms	High-flexibility firms
	(1)	(2)	(3)	(4)	(5)
P_E	−0.053***	−0.053***	−0.066***	−0.079***	−0.039***
	(0.009)	(0.009)	(0.013)	(0.014)	(0.011)
P_E × sigma		0.017**			
		(0.008)			
P_E × sigma (binary)			0.024		
			(0.017)		
Firm FE	✓	✓	✓	✓	✓
Year × Sector FE	✓	✓	✓	✓	✓
Year × Region FE	✓	✓	✓	✓	✓
Observations	75,802	75,802	75,802	39,448	36,354

Notes: All specifications include firm, year-by-sector, and year-by-region fixed effects. Column (4) and (5) report estimates separately for low-flexibility firms and high-flexibility firms, respectively. Standard errors are clustered at the firm level.

sector with sector-by-year fixed effects (ρ_{st}), and any local economic shocks by region-by-year fixed effects (ν_{ct}). Standard errors are clustered at the firm level.

Table 3 reports the results from this analysis. In column (1), we first estimate the effect of energy prices on labor demand across all firms with sector-by-year and region-by-year fixed effects. The estimate indicates that higher energy prices have a negative impact on firms' labor demand. The detrimental impact of energy prices on employment in the French context is in line with the findings from studies that have used the same datasets (e.g., Marin and Vona, 2021; Dussaux, 2020). It is also consistent with the findings in Section 4 that elasticity of substitution substantially is sufficiently below unity. Since labor and energy tend to be complements in most firms, demand for labor is expected to fall when energy prices rise due to the negative output effect.

Next, we test the role of the elasticity of substitution between labor and energy by estimating Eq. (17) with the interaction term. Column (2) reports the results from this specification. The coefficient on the energy prices variable remains close to the previous one. Importantly, consistent with the prediction of our model, the coefficient on the interaction term is positive and significant, implying that the negative impact of higher energy prices is mitigated as the degree of the input substitutability increases.[8] Intuitively, when energy prices increase, firms with higher degrees of the elasticity of substitution between labor and energy may substitute energy by labor, which would offset the negative output impact to some extent. This countervailing channel is more constrained among firms with lower degrees of input substitutability.

In column (3), we also try a binary specification of the input substitutability measure that takes 1 if the firm exhibits a degree of substitutability higher than the median (high-flexibility firms) and 0 otherwise (low-flexibility firms). The coefficient on the interaction term is still positive, although less precisely estimated. In the next columns, we split the sample into high-flexibility and low-flexibility firms according to the binary specification. It is reassuring that the magnitude of the negative impact of energy prices on labor demand is smaller among high-flexibility firms (column (5)) than among low-flexibility firms (column (4)).

We then examine the impact of energy prices on energy consumption and how it relates to the degree of input substitutability between labor and energy. In contrast to the ambiguous effect of energy prices on labor demand, its impact on energy consumption is expected to be unambiguously negative. Moreover, high-flexibility firms are likely to reduce their energy consumption by a *larger* margin in response to higher energy prices because they could substitute away from energy more easily than their counterparts with lower input substitutability when energy prices go up (Prediction 2). To test this, we estimate Eq. (17) using log energy consumption (in TOE) as the dependent variable. The interaction term $P_{E,it} \times \sigma_i$ again captures these differential effects of energy prices across firms with varying degrees of input substitutability.

Table 4 reports the results from this exercise. Column (1) first shows that as expected, higher energy prices lead to lower demand for energy across all firms, controlling for firm fixed effects, sector-by-year and region-by-year fixed effects. In column (2), we include the interaction term between energy prices and the measure of substitutability between labor and energy. The coefficient on the interaction term has the expected negative sign. We make a similar observation in column (3) where we use the binary specification of the measure of input substitutability that takes 1 for high-flexibility firms and 0 for low-flexibility firms. In line with our theoretical model, the negative coefficients indicate that firms reduce energy consumption more as the degree of input substitutability increases. For example, the results in column (3) indicate that the price elasticity of energy consumption is −0.819 for firms with below median flexibility, while it is −1.284 for those with above median flexibility. Estimating elasticities separately for low- and high-flexibility firms (column (4) and (5), respectively) yields similar results.

[8] We attempt to interpret the interaction term by looking at how much the elasticity changes when the substitutability measure increases by 1 standard deviation (1.359) from the mean (0.62). The elasticity at the mean substitutability level is −0.042 (based on the two coefficients in column (2)), while it becomes less negative to −0.018 when substitutability increases by 1 standard deviation.

Table 4
The impact of energy prices on energy demand.

	Dependent variable: energy demand				
	All firms			Low-flexibility firms	High-flexibility firms
	(1)	(2)	(3)	(4)	(5)
P_E	−1.080***	−1.080***	−0.819***	−0.781***	−1.315***
	(0.024)	(0.024)	(0.031)	(0.034)	(0.033)
P_E × sigma		−0.043			
		(0.042)			
P_E × sigma (binary)			−0.465***		
			(0.040)		
Firm FE	✓	✓	✓	✓	✓
Year × Sector FE	✓	✓	✓	✓	✓
Year × Region FE	✓	✓	✓	✓	✓
Observations	76,133	76,133	76,133	39,645	36,488

Notes: Notes: All specifications include firm, year-by-sector, and year-by-region fixed effects. Column (4) and (5) report estimates separately for low-flexibility firms and high-flexibility firms, respectively. Standard errors are clustered at the firm level.

Table 5
The impact of energy prices on labor and energy demand: IV estimates.

	All firms	Low-flexibility firms	High-flexibility firms
	(1)	(2)	(3)
Panel 1: Labor demand			
P_E	−0.142**	−0.177*	−0.114
	(0.059)	(0.09)	(0.076)
First-stage F statistic	1950.12	1269.73	755.26
Observations	62,827	32,979	29,848
Panel 2: Energy demand			
P_E	−0.756***	−0.650***	−0.924***
	(0.077)	(0.097)	(0.118)
First-stage F statistic	1976.07	1296.86	759.48
Observations	63,161	33,178	29,983
Firm FE	✓	✓	✓
Year × Sector FE	✓	✓	✓
Year × Region FE	✓	✓	✓

Notes: All specifications include firm, year-by-sector, and year-by-region fixed effects. Samples used for estimation are indicated above column numbers. Standard errors are clustered at the firm level.

Table 5 reports IV estimates using the shift-share instrument developed in Section 4. Panel 1 reports the impact of energy prices on labor demand. In column (1), the cross-elasticity of −0.142 from the whole sample is similar in magnitude to the previous estimates reported in the literature that range from −0.08 to −0.15 (Deschenes, 2011; Kahn and Mansur, 2013; Marin and Vona, 2021). The IV estimates from the split samples are in line with the FE estimates: the negative impact of energy prices on employment is larger in magnitude among low-flexibility firms than high-flexibility firms.

Panel 2 reports the impact of energy prices on energy demand. We again observe that the estimates give rise to a similar picture: high-flexibility firms reduce their demand for energy by a larger margin than low-flexibility firms (the own-price elasticity of −0.924 in column (3) versus of −0.650 in column (2)). Table OA4 reports results from several robustness checks. First, we try an alternative binary specification for dividing high and low-flexibility firms by defining firms with $\sigma > 1$ as high-flexibility firms and as low-flexibility firms if $\sigma \leq 1$ (Panel 1). Next, we further control for the price of the substitutable good by adding the local wage measure (Panel 2). Finally, in case the exclusion restriction of the instrument that requires the growth in the outcome variables be uncorrelated is violated, we follow Marin and Vona (2021) and explicitly control for the growth in the outcome variables in the pre-sample period (Panel 3). The estimates remain qualitatively similar.

5.3. Discussion

Our findings on the workings of the elasticity of substitution between labor and energy can add to the debate on the economic costs of higher energy prices. First, as criteria to identify firms that are at a higher risk of losing competitiveness due to more stringent environmental regulation, exposure to trade and energy intensity have been commonly used by policy makers (Martin et al., 2014).[9] We believe our analysis suggests another dimension along which the negative impact of energy prices or tighter environmental policies that lead to higher energy prices may differ substantially across different firms. Previous estimates of the energy price elasticity of employment range between −0.08 and −0.15 (Deschenes, 2011; Kahn and Mansur, 2013; Marin and Vona, 2021). However, our estimate of the cross-elasticity among low-flexibility firms is around −0.18, which is larger than the existing estimates (column (2) of Row 1 in Table 5). This suggests that the negative impact of higher energy prices on labor demand can be more severe when we focus on firms that are more constrained in terms of input choices in their production process. In our context, we find that the overall negative employment effects of energy prices are driven by these firms.

We believe this analysis may also offer a potential explanation for the mixed empirical evidence on how rising energy prices affect employment (e.g., Kahn and Mansur, 2013; Martin et al., 2014; Hille and Möbius, 2019; Marin and Vona, 2021; Dussaux, 2020). Given the large differences across the samples used in prior studies and the importance of flexibility in input substitution in determining the net impact of higher energy prices on employment, the sample composition in terms of the elasticity of substitution exhibited by firms could lead to diverging estimates for the impact of energy prices on labor demand.[10]

5.4. The impact of energy prices on R&D activities

Previous studies have shown that environmental regulation may bring about compositional changes in the labor force, favoring workers with ‘green’ skills over low-skilled manual workers (Vona et al., 2018; Marin and Vona, 2019, 2021). In a similar spirit, our model posits that demand for R&D labor (green and high-skilled) might also change in response to higher energy prices, which also depends on the elasticity of substitution between labor and energy (Prediction 3). To investigate this, we bring in additional data on resources devoted to research and development in firms to our main dataset, which leads to a much smaller sample size of around 3100 firms.[11] Using this data, we look at changes in R&D labor in response to rising energy prices on this smaller sample of firms.

We do not find any discernible impact of energy prices on R&D labor across all firms or among high-flexibility firms, but do observe a negative impact among low-flexibility firms which is consistent with our theoretical prediction (Table OA6 in Online Appendix). Despite the smaller sample size, this suggests potentially long-term negative effects of rising energy prices on firms' growth prospects, particularly those with limited capacity for input substitution (e.g., Audretsch and Belitski, 2020). We believe a deeper investigation into firms' innovation activities, for instance using patent data, can shed further light on the long-run dynamic implications of higher energy prices for firms.

6. Conclusion

Previous studies on the impact of energy prices on employment have so far provided mixed empirical results. Thus, to deepen our understanding of how firms adjust labor demand in response to higher energy prices, this paper investigates arguably the most important factor behind how and why firms adjust labor demand in response to changes in energy prices: the degree of substitutability between the two inputs.

Using firm-level data from the French manufacturing sector, we provide three main findings. First, we provide micro empirical estimates of the elasticity of substitution between labor and energy of around 0.6. This implies that labor and energy tend to be complements in most firms. Second, the negative impact of energy prices on labor demand is mitigated among firms with higher levels of input substitutability than among those with lower levels of input substitutability. Finally, the opposite is observed with respect to energy consumption. Intuitively, high-flexibility firms tend to reduce their energy consumption by a larger margin when energy prices are higher. In addition, we observe from a subset of firms that energy prices have a negative impact on R&D activities only among low-flexibility firms.

Our analysis adds a fresh and yet intuitive angle to the on-going debate on the economic costs of market-based environmental policy that leads to higher energy prices. Yet, there is much room for improvement and future research. For instance, we observe from the data a large degree of dispersion in the elasticity of substitution between labor and energy and have found that it determines the magnitude of the negative impact of higher energy prices on labor demand. However, little is known about the determinants of the input substitutability exhibited by firms. Even within the same industry, why do some firms have higher or lower levels of input substitutability than others? Does input substitutability change over time? Given its crucial impact on firms' input demand decisions, understanding the determinants of input substitutability would enhance our knowledge in firms' operation in changing regulatory environments.

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[9] For instance, the EU Commission uses the level of trade exposure to non-EU countries to define sectors and subsectors at significant risk of carbon leakage and provide these sectors with a higher share of free allowances in the EU Emissions Trading Scheme.

[10] For example, Kahn and Mansur (2013) use a sample of US manufacturing plants, Martin et al. (2014) UK manufacturing plants, Hille and Möbius (2019) Irish manufacturing firms, and Marin and Vona (2021) French manufacturing plants. Although there is hitherto no existing evidence on cross-country differences in the elasticity of substitution between labor and energy, the cross-country variation in the elasticity of substitution between labor and capital (Yuhn, 1991; Klump et al., 2012) hints at similar potential differences in the elasticity of substitution between other inputs.

[11] The data comes from *Enquete sur les Moyens Consacrés à la Recherche* that provides detailed firm-level information on R&D activities including R&D personnel that includes researchers and engineers, technicians, workers, administrative staff devoted to R&D activities. The sample consists of firms that are likely to carry out in-house R&D work, regardless of their sector and size. On average, approximately 10,000 firms are surveyed every year. Descriptive statistics is presented in Table OA5.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2024.102934.

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