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

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Abstract

This paper adds a fresh angle to the on-going debate on the potential negative employment effect 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, we provide rigorous micro estimates of this parameter that point to strong complementarity between labor and energy. We then provide clear evidence for the empirical, as well as theoretical, relevance of the elasticity of substitution in understanding the effect of environmental policies on employment.

Keywords: market-based regulation, employment, elasticity of substitution.
JEL Classification: Q40, Q54, Q55, O33.

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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.

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 energy by labor in response to higher energy prices. In this case, the negative output effect would be less pronounced among these firms. It 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. Manufacturing and understanding how it responds to changing energy prices is of importance given that it takes over 20 percent of total energy consumption in France (Eurostat, 2018). Furthermore, the data provide 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 much attention to endogeneity concerns (e.g., Berndt and Wood, 1975; Koetse et al., 2008). Thus, we aim to provide rigorous micro estimates of this key parameter.

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 examine how firms' responses to energy prices differ according to their flexibility in input substitution. The measure is calculated by the percentage change in relative quantities of energy and labor due to a change in their relative prices. In both parts of the analysis, we follow earlier studies and account for the endogeneity of firm-level energy prices by using the weighted sum of national fuel prices using time-invariant fuel shares at the firm level as weights (Linn, 2008; Sato et al., 2019; Marin and Vona, 2019, 2021; Jo, 2020).

We report four main empirical findings. First, labor and energy tend to be complements in most firms with the estimated elasticity of substitution between labor and energy ranging between 0.61 and 0.80. Although we observe a fair amount of heterogeneity across industries, we reject the hypothesis that the elasticity of substitution is equal to unity for 14 out of 18 industries. Second, we find evidence for the theoretical prediction that the negative impact of energy prices on labor demand is less negative 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 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. We observe from the data that the overall negative employment effects of rising energy prices are driven by these firms.

Third, 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. Finally, we also provide evidence that low-flexibility firms also tend to reduce labor devoted to R&D activities when energy prices rise, while high-flexibility firms do not, which has strong implications for their long-term growth. 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). The analysis yields novel findings that the elasticity of substitution plays an important role in determining the magnitude of the impact of increasing energy prices on employment and energy consumption. Notably, we find that the negative employment effects of rising 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). Our analysis differs from most papers in the literature as they tend to focus on the capital-energy substitutability, while we focus on the elasticity of substitution between *labor* and energy faced by firms. Also, the bulk of the literature estimates translog cost functions without paying much attention to endogeneity concerns. In contrast, we estimate first-order conditions from firms' profit maximization problem and account for endogeneity arising from firm-level input prices. Our analysis suggests that despite large dispersion, labor and energy tend to be strong complements in most firms with the estimates of the elasticity of substitution substantially below one. This result is in line with Hassler et al. (2012) that report a low (close to zero) elasticity of substitution between energy and non-energy inputs (labor and capital).

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. Section 6 focuses on demand for R&D labor and Section 7 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. 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. Indeed, we will provide empirical evidence below that wages are sticky i.e. they do not change instantaneously. 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. 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 $1/\omega_i$. 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:

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

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:

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

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 question 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 in the second we have $\hat{N}_i < 0$ where the size of the effect depends on determinants like 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:

Prediction 1: Rising energy prices reduce labor demand in manufacturing. Yet, firms with a high input substitution elasticity experience lower employment reduction.

Prediction 2: Rising energy prices reduce energy demand in manufacturing. Moreover, high-flexibility firms reduce their energy consumption by a larger amount.

Prediction 3: Rising energy prices reduce labor demand in research. The size of the impact is determined by how flexible wages are. When wages are sticky, firms with a high input substitution elasticity experience lower or even no employment reduction. When wages are flexible, firms with a low input substitution elasticity experience lower or even no employment reduction.

We bring these predictions to the data in the remainder of the paper.

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.[1] 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 financial 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

[1]The sample covers all firms that are required to make tax declarations to the French Ministry of the Economy and Finance. 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.

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. Thus, we begin the analysis by estimating this key parameter from our data.

4.1 Specification

We identify the elasticity of substitution by using the log-linear relationship between the firm's relative input quantities and relative prices from equation (7):

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

where E_{it}/N_{it} is the input ratio of energy consumption to total labor of firm i in year t. The dependent variable is regressed on the firm-specific price ratio $W_{it}/P_{E,it}$. The specification also includes δ_t, $\omega_{s(i)}$ and $\phi_{c(i)}$ that control for unobservable year-, industry-, and region-specific shocks, respectively. We also try a more demanding year by industry and year by region fixed effects. Finally, firm fixed effects η_i control for time-invariant firm characteristics such as persistent productivity differences (not idiosyncratic shocks) across firms that may be correlated with their input choices. Standard errors are clustered at the firm level.

The coefficient of interest β_1 captures the elasticity of substitution between labor and energy through the changes in relative prices that the firm faces. 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. In the section below, we first report the fixed-effects estimates as a starting point. Next, we discuss potential time-varying omitted variable bias and report estimates using instruments for the relative price ratio.

4.2 Fixed-effects estimates

Table 2 reports the estimates of the elasticity of substitution between labor and energy from estimating equation (15). In column (1), we start by including only firm fixed effects to control for persistent firm characteristics that may be correlated firms' input choices. The estimate is below one around 0.8, implying that the two production inputs, labor and energy, are complements. Adding year, sector, region fixed effects or year by sector and year by region fixed effects yields similar estimates (column (2) and (3)). Controlling for firms' age as a potential firm characteristics that might be correlated with their input substitution capacity does not significantly affect the magnitude of the estimate (column (4)).

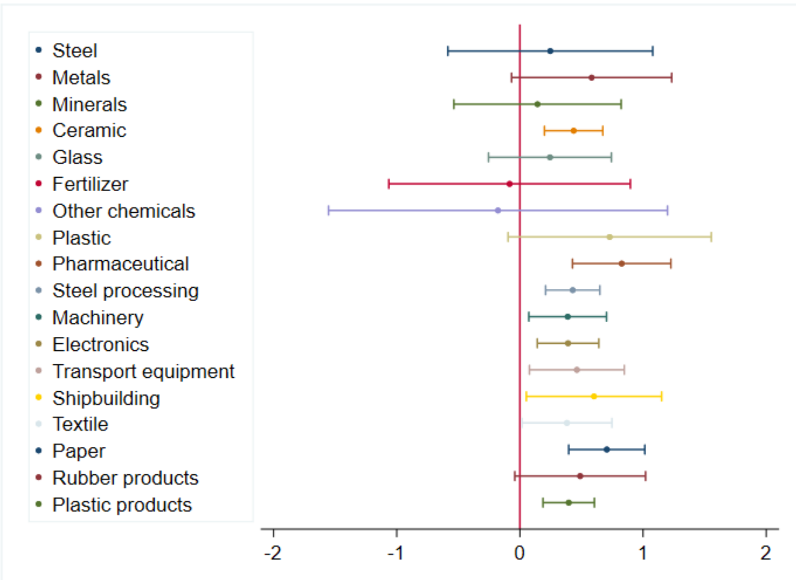
We further examine the elasticity of substitution between labor and energy by industry at the two digit level (according to NAF rev.2, the French classification of economic activities). Figure 1 graphically reports the estimates and 95 percent confidence intervals for 18 industries from the specification that includes firm and year fixed effects (the cement sector is dropped due to a small number of observations). Although we observe a fair degree of heterogeneity across industries, all industries display point estimates of the elasticity of substitution below one and we reject the hypothesis that the elasticity of substitution is equal to one for 14 out of 18 industries. The estimates also tend to be precisely estimated; 13 out of 18 coefficients on the relative prices variable are statistically significant at conventional levels.

Table 2: Elasticity of substitution between labor and energy

	Dependent variable: $\log \frac{E_{it}}{N_{it}}$			
	(1)	(2)	(3)	(4)
$\log \frac{W_{it}}{P_{E,it}}$	0.809***	0.804***	0.807***	0.802***
	(0.017)	(0.019)	(0.019)	(0.020)
Age				0.000
				(0.000)
Firm FE	✓	✓	✓	✓
Year FE		✓		
Sector FE		✓		
Region FE		✓		
Year × Sector FE			✓	✓
Year × Region FE			✓	✓
Observations	75,734	75,734	75,734	70,305
R^2	0.23	0.24	0.25	0.27

Notes: Estimates from equation (15). Included fixed effects are marked for each column. Standard errors are clustered at the firm level.

Figure 1: The elasticity of substitution between labor and energy by sector



Notes: The graph plots point estimates of the elasticity of substitution by two digit industry (according to NAF rev.2), as well as 95 percent confidence intervals.

4.3 Endogeneity

A remaining concern with the fixed-effects estimates is that 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.[2]

Before we propose instruments, we examine variation in the potentially endogenous input price ratio to gain a sense of the salience of bias arising from each element that forms the ratio, namely, firm-level unit price of energy and firm-level wage. We find that the firm-level unit price of energy varies substantially across years, while firm-specific wage tends to be strongly persistent over time. For instance, the firm-specific one, three, five, and ten year autocorrelation coefficient for wage after controlling for sector fixed effects are 1.201, 0.905, 0.940, 0.957, respectively, remaining strongly correlated over long time periods. In contrast, the same coefficients for energy prices are 0.858, 0.783, 0.691, 0.306, respectively, which shows that autocorrelation in energy prices diminishes rapidly over time. From these observations, we gather that energy price is likely to be more endogenous than wage, responding more strongly to year-to-year unobservable shocks within firms.

Equipped with this knowledge, we propose one instrument for each element of the input price ratio. First, as an instrument for the firm-level energy price, we consider 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.[3]

[2]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.

[3]The included fuels are electricity, steam, natural gas, other types of gas, coal, coke, butane and propane,

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 *growth* in the input ratio, rather than *level*. In Table A1, we show that the pre-sample fuel shares used to construct the instrument are not correlated with growth in the input ratio (log E/N) in subsequent years.[4]

Although wage appears to be persistent over time and therefore less likely to be endogenous than energy price, the potential endogeneity of firm-specific wage cannot be ruled out. Thus, we follow Raval (2019) and use local wage to instrument for firm-specific wage. Since the local wage is largely formed by local employment conditions, it can isolate variation in the firm-specific wage that is 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.

4.4 IV estimates

Table 3 contains estimates that account for time-varying omitted variable bias with the instruments developed above.[5] In column (1), we first use the weighted sum of national fuel prices $P_{E,it}^{IV}$ (in log) to instrument for the log price ratio, given that the energy price component is a more worrisome source of endogeneity. Once instrumented, the estimates 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 additional instrument.[6] The point estimates remains similar in magnitude. In specifications that use both instruments (column (2) and (3)), the Hansen J statistics suggests we fail to reject the null hypothesis that all instruments are exogenous (i.e., p-value 0.279 in column (2)).

From the estimates, we observe that labor and energy tend to be complements in the production process of firms. Our estimates are qualitatively comparable with the results

heavy fuel oil, heating oil and other petroleum products.

[4]The pre-sample year is 1994 and consequently, the sample for IV estimation runs from 1995 to 2015.

[5]Relevant first stage results are reported in Table A3.

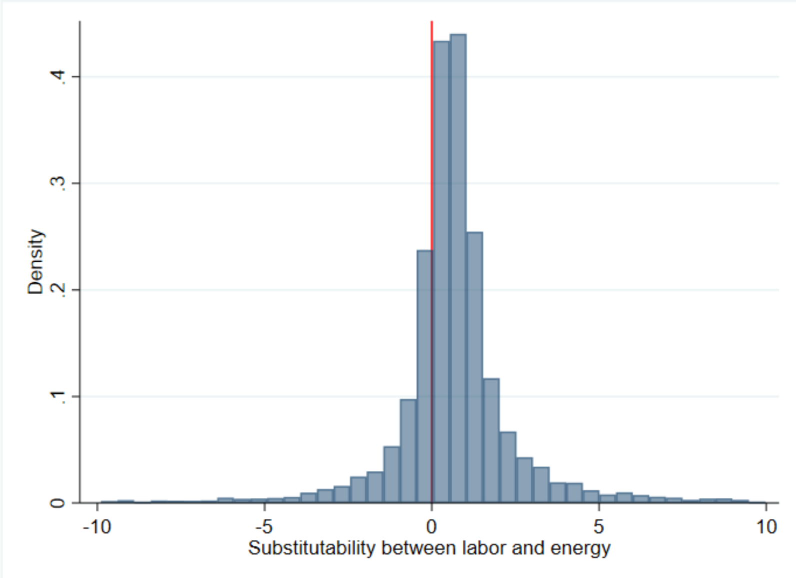
[6]Note that year by region fixed effects cannot be included when the local wage measure is used as an instrument as it varies at the region-year level.

Table 3: Elasticity of substitution between labor and energy: IV estimates

	Dependent variable: $\log \frac{E_{it}}{N_{it}}$		
	(1)	(2)	(3)
$\log \frac{W_{it}}{P_{E,it}}$	0.614***	0.624***	0.638***
	(0.072)	(0.070)	(0.077)
Firm FE	✓	✓	✓
Year FE	✓	✓	
Sector FE	✓	✓	
Region FE	✓	✓	✓
Year × Sector FE			✓
Observations	62,763	62,763	62,763
R^2	0.23	0.23	0.25
First-stage F statistic	1393.73	716.37	561.762
Hansen J statistic		1.169	1.173

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

Figure 2: Distribution of the measure of substitutability between labor and energy



Note: The graph shows the distribution of the firm-level measure of the elasticity of substitution between labor and energy.

in Hassler et al. (2012) 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. Equipped with this knowledge, we move on to our next analysis where we examine the empirical relevance of the elasticity of substitution between labor and energy in investigating how firms respond to changing energy prices.

5 The impact of energy prices on labor and energy demand

5.1 A firm-level measure of input substitutability

To explicitly account for the role of the elasticity of substitution, we need a firm-level measure that allows us to investigate how firms' response to changing energy prices differ depending on their input substitution capacity. Thus, we *construct* a firm-level measure of the elasticity of substitution between labor and energy from our data defined by the percentage change in relative quantities of energy and labor due to a change in their relative prices:

$$\sigma = \frac{\Delta \log \left(E_{it}/N_{it}\right)}{\Delta \log \left(W_{it}/P_{E,it}\right)} \tag{17}$$

Figure 2 depicts the distribution of the firm-specific median of the elasticity of substitution between labor and energy with a reference line at $\sigma = 0$. It is readily observed that there exists a large degree of dispersion across firms. Over 40 percent of firms display the elasticity of substitution between 0 and 1. On the other hand, slightly over 30 percent of firms exhibit the elasticity of substitution greater than 1. The mean (median) of the measure is 0.670 (0.596). The descriptive statistics fall squarely in the range of the estimates reported in the previous section, which again implies that labor and energy tend to be complements in production in most firms.

Table A2 shows how the measure of input substitutability correlates with other firm characteristics. The measure of input substitutability tends to be negatively correlated with measures 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).

5.2 Baseline estimation

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:

$$\log N_{ijct} = \beta_0 + \beta_1 \log P_{E,it} + \beta_2 \log P_{E,it} \times \sigma_i + \mu_i + \rho_{jt} + \eta_{ct} + \epsilon_{ijct}, \tag{18}$$

The dependent variable N_{ijct} measures log employment in firm i in sector j in region c in period t. The interaction term between $P_{E,it}$ and σ_i captures the counteracting substitution effect that regulates the net impact of energy prices on labor demand. Note that we use the firm-specific median of the measure of substitutability, σ_i, constructed in the previous section since the measure can change over time with much noise. The regression also controls for any permanent observed or unobserved firm characteristics with firm fixed effects (μ_i), annual fluctuations in each sector with sector-by-year fixed effects (ρ_{jt}), and any local economic shocks by region-by-year fixed effects (η_{ct}). Standard errors are clustered at the firm level.

Table 4 reports the results from this analysis. In column (1), we first estimate the effect

Table 4: 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		0.000**			
		(0.000)			
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.

of energy prices on labor demand across all firms with sector-by-year and region-by-year fixed effects. The coefficient 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 are 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 equation (18) with the interaction term. Column (2) reports the estimate 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, indicating that the negative impact of higher energy prices is mitigated as the degree of the input substitutability increases. 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.[7] It is reassuring that the magnitude of the negative impact of energy prices on labor demand is substantially smaller among high-flexibility firms (column (4)) than among low-flexibility firms (column (5)).

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 (Prediction 2). To test this, we estimate equation (18) using log energy consumption (in TOE) as the dependent variable. The interaction term $P_{E,it} \times \sigma_i$ again

[7]Although we divide the sample around the median, the number of observations is still larger for the low-flexibility group as they tend to be larger (as we have seen in Table A2) and larger firms are more often surveyed than smaller firms in the EACEI.

Table 5: 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)
$P_E \times$ sigma		-0.000			
		(0.000)			
$P_E \times$ sigma (binary)			-0.465***		
			(0.040)		
Firm FE	✓	✓	✓	✓	✓
Year $\times$ Sector FE	✓	✓	✓	✓	✓
Year $\times$ 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.

captures these differential effects of energy prices across firms with varying degrees of input substitutability.

Table 5 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.

Finally, we split the sample according to this binary specification and examine the price elasticity of energy consumption separately for high-and low flexibility firms. Comparing estimates from these two groups of firms, we observe that high-flexibility firms are more responsive to energy prices with more negative price elasticities of energy consumption than those estimated from low-flexibility firms (-1.315 in column (5) versus -0.781 in column

(4)), which is consistent with the observations from the interaction terms in column (2) and (3). The exercise with the split samples and the significance and expected signs of the coefficients on the interaction terms, both in relation to the labor and energy demand, point to the empirical relevance of the elasticity of substitution between labor and energy in studying firms' response to changes in energy prices.

5.3 IV estimation

Similar sources of endogeneity as in the estimation of the elasticity of substitution between labor and energy continue to be a concern. Regarding energy demand, both demand and productivity shocks would lead to downward bias.[8] On the other hand, the direction of the potential bias regarding labor demand is less straightforward. For instance, given the complementarity between labor and energy, factor-specific productivity shocks may lead to downward bias. Positive energy efficiency shocks, for example, would lower energy consumption and labor demand simultaneously due to the complementarity and increase the unit cost of energy, leading to downward bias. However, technical change that substitutes more expensive energy by labor is likely to lead to upward bias (Hassler et al., 2012), which makes the net effect of the bias ambiguous.[9] To address these endogeneity concerns, we use the instrument developed in Section 4, the weighted sum of national fuel prices using the pre-sample fuel shares as weights, to account for the endogeneity of firm-level energy prices.[10]

Panel 1 of Table 6 shows the estimation results on the impact of energy prices on labor demand on the split samples of low- and high-flexibility firms. Column (1) first reports the IV estimate from the whole sample. The cross-elasticity of -0.142 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 continue to provide support for the prediction of our theoretical model. We find that the negative impact of energy prices on employment is larger in magnitude among

[8]Positive demand shocks increase energy demand and lower the unit cost of energy through larger quantity discounts, leading to downward bias. Similarly, positive energy efficiency shocks would reduce energy demand and increase the unit cost of energy, leading to downward bias.

[9]This type of technical change would still lead to upward bias in the estimation of the elasticity of substitution in Section 4 by decreasing the input ratio and the price ratio simultaneously.

[10]As discussed in Section 4.3, the validity of the instrument requires the growth in the outcome variables be uncorrelated with the pre-sample fuel shares. Explicitly examining the correlation in Table A1 reveals that the pre-sample shares of electricity and natural gas, the two most popular fuels, tend to be correlated with the growth in energy consumption and labor demand within firms. This raises the concern that the pre-sample shares and therefore the instrument may not be exogenous. To probe the salience of the potential bias, we explicitly control for the growth in energy consumption and labor demand in the pre-sample period and find that our estimates are similar in magnitude (Panel 3 in Table A4).

Table 6: The impact of energy prices on labor and energy demand: IV estimates

	All firms (1)	Low-flexibility firms (2)	High-flexibility firms (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.

low-flexibility firms than among high-flexibility firms.

Panel 2 reports the estimation results on the impact of energy prices on energy demand. We again observe that the estimates give rise to a similar picture of sharply different responses of low- and high-flexibility firms in terms of their energy demand in response to higher energy prices: 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)). Furthermore, we note that the IV estimates tend to be less negative compared to the estimates in Table 5, confirming the predicted downward bias from unobservable factors. Table A4 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).

We believe these findings provide strong support for the empirical relevance of the elasticity of substitution in regulating the net effect of changing energy prices on input choices.

5.4 Discussions

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).[11] 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 6).[12] This suggests that the negative impact of higher energy prices on labor demand can be more severe when we focus on firms with limited input substitution capacity in their production and the overall negative employment effects of rising energy

[11]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.

[12]The estimate from the whole sample in column (1) (-0.14) is within the range of existing estimates.

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.[13]

6 The impact of energy prices on R&D activities

6.1 Survey of Resources Devoted to Research

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).[14] 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). In order to specifically examine the change in R&D labor, we bring in a third dataset the 'Enquete sur les Moyens Consacrés à la Recherche', a survey on resources devoted to research and development in firms. 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.

The survey makes available 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. We use this information to specifically look at changes in R&D labor in response to rising energy prices. One disadvantage of the dataset is that it is not a representative sample of manufacturing firms as the EACEI is. Thus, the intersection between the two surveys (note that the FARE is a census) is relatively small. Merging the R&D survey leads to a reduction in sample size from around 11,000 firms in the main dataset

[13] 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.

[14] In Vona et al. (2018), green skills are defined as engineering skills for design and production of technology, and managerial skills for setting up and monitoring environmental organizational practices.

to around 3,100 firms over the same time period (1994-2015). Descriptive statistics of this smaller sample of firms is presented in Table A5.

6.2 Estimation results

We examine how the impact of energy prices on R&D labor demand may differ across firms with different degrees of input substitution capacity. Table 7 reports the results. First, we do not find a discernible impact of energy prices across all firms when we focus on labor devoted to R&D activities in column (1) of Panel 1. In the next two columns, we examine the impact separately for high- and low-flexibility firms. Column (2) and (3) provide evidence that high-flexibility firms tend not to reduce the size of their R&D personnel, while low-flexibility firms do so. The findings are in line with our third theoretical prediction that when wages are sticky as we see from the data (see discussion in Section 4.3), the same reasoning as in the case of total labor demand applies to research labor demand: high-flexibility firms substitute more expensive energy by labor also in their research activities while low-flexibility firms are constrained to do so. In Panel 2, we restrict R&D personnel to researchers only (excluding technicians and administrative staff) and find similar impacts. High-flexibility firms are largely unresponsive in terms of their demand for high-skilled researchers when energy prices increase, while low-flexibility firms tend to reduce their research workforce. Given the importance of R&D on firms' long-term growth (e.g., Audretsch and Belitski, 2020), these findings highlight, not only short-term, but also potentially long-term negative implications of rising energy prices on firms, particularly those with limited capacity in input substitution.

7 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, in this paper we bring to the fore 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 four main findings. First, we provide micro empirical estimates of the elasticity of substitution between labor and energy that range between 0.45 and 0.80. This implies that labor and energy tend to be strong complements in most firms. Second, the negative impact of energy prices on labor demand is less negative among firms with higher levels of input substitutability than

Table 7: The impact of energy prices on R&D labor demand: IV estimates

	All firms (1)	Low-flexibility firms (2)	High-flexibility firms (3)
Panel 1: All R&D personnel			
P_E	-0.030	-0.935*	1.017
	(0.386)	(0.495)	(0.623)
First-stage F statistic	257.74	137.58	94.07
Observations	10,990	6,060	4,930
Panel 2: Researchers only			
P_E	-0.359	-1.144**	0.366
	(0.375)	(0.456)	(0.661)
First-stage F statistic	257.74	137.58	94.07
Observations	10,990	6,060	4,930
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.

among those with lower levels of input substitutability. Third, the opposite is observed with respect to energy consumption. Intuitively, high-flexibility firms tend to reduce their energy consumption by a larger margin in response to higher energy prices. Finally, we also provide suggestive evidence that energy prices have a negative impact on R&D activities only among low-flexibility firms, which raises a concern over their long-term competitiveness.

Our analysis adds a fresh and yet intuitive angle to the old debate regarding the economic costs of higher energy prices or market-based instruments that lead 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 how firms adjust their input demands in response to input prices, understanding the determinants of input substitutability would enhance our knowledge in firms' operation in changing environments.

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Appendix

Table A1: Correlates between the initial fuel shares in 1994 and growth in firm characteristics in subsequent years

Correlation between the share of electricity and growth in firm characteristics					Correlation between the share of natural gas and growth in firm characteristics				
Growth in 1995					Growth in 1995				
	E share	E	N	E/N		G share	E	N	E/N
E share	1.00				G share	1.00			
E	0.11*	1.00			E	-0.05*	1.00		
N	0.04*	0.07*	1.00		N	-0.02	0.07*	1.00	
E/N	0.01	0.01	0.01	1.00	E/N	0.00	0.02	0.01	1.00
Growth in 1996					Growth in 1996				
	E sharec	E	N	E/N		G share	E	N	E/N
E share	1.00				G share	1.00			
E	0.03*	1.00			E	-0.03	1.00		
N	0.05*	0.07*	1.00		N	-0.03*	0.07*	1.00	
E/N	0.00	-0.00	0.02	1.00	E/N	-0.01	-0.00	0.02	1.00
Growth in 1997					Growth in 1997				
	E share	E	N	E/N		G share	E	N	E/N
E sharec	1.00				G share	1.00			
E	0.07*	1.00			E	-0.02	1.00		
N	0.03*	0.04*	1.00		N	-0.00	0.04*	1.00	
E/N	-0.01	0.01	0.00	1.00	E/N	0.01	0.01	0.00	1.00

Sources: EACEI, FARE 1994-1995. E denotes total energy consumption, N denotes labor demand, and E/N denotes the ratio of energy to labor. All correlation coefficients reflect a correlation between the growth in the variables (in log) in the specified year and the share of fuels observed in 1994. * signifies significance at 5 percent level.

Table A2: Correlation between the measure of input substitutability and firm characteristics

	σ	Value added	Output	N	E	P_E	W
σ	1						
Value added	-0.008*	1					
Output	-0.008*	0.114*	1				
N	-0.015*	0.208*	0.781*	1			
E	0.002	0.137*	0.605*	0.616*	1		
P_E	-0.004	-0.060*	-0.174*	-0.224*	-0.601*	1	
W	0.004	0.149*	0.392*	0.150*	0.183*	0.104*	1

Notes: EACEI and FARE, 1994-2015. σ denotes the constructed measure of input substitutability. N and E denote the number of employees and total energy consumption, respectively. P_E and W denote the unit price of energy and wage, respectively. * signifies significance at 5 percent level.

Table A3: First-stage: the relationship between the instruments and the endogenous variable

	Dependent variable: $\log \frac{W_{it}}{P_{E,it}}$		
	(1)	(2)	(3)
$\log P^{IV}_{E,it}$	-0.479***	-0.478***	-0.443***
	(0.028)	(0.028)	(0.028)
log local wage		0.063***	0.063***
		(0.024)	(0.025)
Firm FE	✓	✓	✓
Year FE		✓	
Sector FE		✓	
Region FE		✓	✓
Year × Sector FE			✓
Observations	62,763	62,763	62,763
R^2	0.12	0.12	0.13

Notes: First stage results for IV estimation of equation (15) with instruments. Included fixed effects are marked for each column. Column (1) uses the fixed weight instrument explained in the main text. Column (2) and (3) use both instruments. Standard errors are clustered at the firm level.

Table A4: The impact of energy prices on labor and energy demand: Robustness checks

	Dependent variable: Labor demand		Dependent variable: Energy demand	
	Low-flexibility firms (1)	High-flexibility firms (2)	Low-flexibility firms (3)	High-flexibility firms
Panel 1: Alternative binary specification				
P_E	-0.253**	-0.110*	-0.668***	-1.066***
	(0.121)	(0.064)	(0.080)	(0.174)
First-stage F statistic	1775.330	344.062	1804.198	346.503
Observations	47,015	15,812	47,262	15,899
Panel 2: Controlling for local wage				
P_E	-0.225**	-0.149*	-0.676***	-0.942***
	(0.094)	(0.077)	(0.096)	(0.118)
First-stage F statistic	1319.75	793.42	1344.31	798.40
Observations	32,979	29,848	33,178	29,983
Panel 3: Controlling for pre-trends				
P_E	-0.178**	-0.107	-0.660***	-0.961***
	(0.090)	(0.075)	(0.096)	(0.115)
First-stage F statistic	1275.03	755.24	1307.40	790.83
Observations	32,904	29,781	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. In Panel 3, pre-trends in the outcome variables are calculated by interacting a linear time trend with the growth rate in the outcome variables between the pre-sample period (1994) and the first year of the sample. Standard errors are clustered at the firm level.

Table A5: Descriptive statistics: R&D sample

Variables	Mean	SD	p10	p90
Energy consumption (E)	1,251	1,914	84.85	3,400
Unit price of energy (P_E)	0.637	0.174	0.436	0.852
Total labor (N)	361.9	704.9	58	761
Output	71,265	230,620	7,028	151,308
Value added	24,370	65,758	2,773	52,329
Wage (W)	30.40	12.55	21	40.90
RD labor	33.86	147.9	2	66
Researcher	16.24	96.19	1	28

Sources: EACEI, FARE R&D Survey, 1994-2015.

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