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Assessing the Rebound Effect in Energy Intensive Industries:

A Factor Demand Model Approach with Asymmetric Price Response[*]

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[*] Financial support from the Swedish Energy Agency is gratefully acknowledged.

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Abstract

The purpose of this paper is to analyze the direct rebound effect potentially prevailing in energy intense industries. The rebound effect represents economic mechanisms that will offset energy savings from energy efficiency improvements. For this purpose, a factor demand model is applied incorporating an asymmetric energy price response. Asymmetric prices imply that firms respond more strongly to energy price increases than to energy price decreases. In the empirical model we use a firm level, unbalanced panel covering the years 2001 to 2012 and four major Swedish energy-intensive industries; pulp and paper, iron and steel, chemical, and mining. The result indicates that the rebound effect is considerable in these industries. To mitigate this effect, the results suggest that policies stimulating an increase in energy efficiency should be combined with a raise in energy taxes.

JEL: Q41; Q48

Key words: Asymmetric price response; Energy efficiency; Factor demand model; Own-price elasticities; Voluntary Energy Efficiency Programs; Rebound effect.

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1. Introduction

In this paper the rebound effect of energy efficiency improvement is empirically addressed. The challenge of climate change, together with energy security of supply concerns, has spurred an increased societal interest in energy efficiency. This has resulted in an EU energy efficiency target of 20 percent by 2020 (Directive 2012/27/EU), and national goals for individual member states. For Sweden the goal stipulates that energy intensity, i.e., the energy use ratio to produced output, is to decrease by 20 percent during the period 2008-2020 (Government Bill 2008/09:163).

These 2020-goals are currently being extended to the year 2030. As such, an indicative target at the EU level of 27 percent energy efficiency improvement was set in 2014 (EC, 2014). However, in November 2016 the European Commission launched an energy package instead suggesting a binding energy efficiency target of 30 percent by 2030. The package includes a revision of the EU Energy Efficiency Directive, and as such an extension to the year 2030 of the energy savings requirements specified in Article 7 of the Directive. In this respect, long term energy efficiency savings that reduce the cost for consumers, whilst increasing the security of supply, is regarded as important by the EU. The Commission declares that "the most efficient energy is the one which is not consumed – as it results in less energy use."[1] Hence, such an EU ambition declares the importance of not implementing measures resulting in significant rebound effects.

Sweden has declared that an energy efficiency target for the period 2020-2030 will be formulated and approved no later than 2017. In line with this, in January 2017 the Swedish Energy Commission put forward a suggestion that a specific energy efficiency program corresponding to PFE should be reinstated for energy-intensive industries, provided that it is possible to fund the program in a responsible manner. (Government Bill 2017:2). However, for such program to be successful in reducing energy consumption depends primarily on two conditions: First, the program must lead to energy efficiency investments that would not otherwise have been implemented and, second, the resulting improvements in efficiency must not lead to any major rebound effect. In the present paper, we focus the latter condition.

Lundgren et al. (2016) found that there is a considerable potential for energy savings in the Swedish manufacturing industry. However, actual reduction in energy consumption from increasing energy efficiency will depend on the *rebound effect*. The rebound effect represents

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[1] https://ec.europa.eu/energy/sites/ener/files/documents/technical_memo_energyefficiency.pdf.

economic mechanisms that will offset energy savings from energy efficiency improvements (Sorrell, 2014). Then, if the reason for increasing energy efficiency is to reduce energy consumption it is necessary to consider the rebound effect. However, although empirical studies confirm the existence of this effect, and that there is a political concern about its existence, the concern is often not translated into real political action (Vivanco et al., 2016).

The purpose of the present study is to estimate the rebound effect in Swedish Energy intensive industries. In Sweden, the industrial sector accounted for 38 percent of total final energy use in 2013, of which the energy intensive process industries; pulp and paper, iron and steel, chemical and the mining industries used about 79 percent.[2]

No specific energy efficiency targets are formulated for the manufacturing industry. Instead, different policies, such as energy taxes have been implemented to promote a more efficient energy use (Swedish Energy Agency, 2012). However, the industry often meets reductions or exemptions from the general energy tax level. Also, different sorts of voluntary agreements focused on industrial process energy use are to be found in several European countries such as, e.g., in Belgium, Denmark, Estonia, Ireland, Slovenia, Sweden and the Netherlands.

For instance, in Sweden the Program for Energy Efficiency Improvement in Energy-Intensive Industry (PFE) was launched in January 2005 and lasted until 2012.[3] PFE was a five year program and firms that participated were fully exempted from energy taxation on electricity[4]. In return, within the two first years, the firms committed to introduce an energy management system and mapping the potential to improve energy efficiency. They also committed to carry out all the improvements that the mapping revealed before the program expired (Swedish Energy Agency, 2012).

The effectiveness of voluntary programs such as PFE has been questioned. According to the Swedish National Audit Office (2013), it is doubtful that PFE led to significant energy efficiency improvements. Mansikkasalo and Söderholm (2013) found that significant investments in order to improve energy efficiency were not realized. Similarly, in their analysis of the Dutch program, Rietbergen et al. (2002) found that much of the energy savings in the Netherlands cannot be attributed to the program.

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[2] www.energimyndigheten.se/statistik/industri-och-naring/?currentTab=1#mainheading

[3] The second program period was launched on 1 July 2009. Qualified firms were able to apply for participation in the second period until December 2012 (and hence will then attend until the year 2017).

[4] The Swedish tax amounts to EUR 0.5/MWh, which is the lowest level approved by EU´s Energy Tax Directive.

One reason for the voluntary programs not resulting in any significant energy savings is that they introduce an inefficient selection mechanism. For instance, Boyd and Curtis (2014) examined management practices in US firms and found that the relationship between energy savings and good management is most profound in energy-intensive firms. This indicates that the firms potentially in need of better energy management are not always the ones participating in the voluntary programs.

In order to estimate the magnitude of the rebound effect in Swedish energy intensive industries, we employ a factor demand model to estimate own price elasticities for various energy inputs in production; fossil fuels, non-fossil fuels, and electricity. We also estimate cross price elasticities between these energy inputs and capital and labor.

Studies that estimate the rebound effect in manufacturing industries are few. Our study contributes to the literature by adding to the evidence on: (*i*) the magnitude of the direct rebound effect in energy intensive industries; pulp and paper, iron and steel, chemical, and mining. For that purpose, we have a unique and detailed data set at firm level, covering the period 2001-2012; (*ii*) we employ a novel price asymmetric approach to allow for energy demand responding differently to increasing and declining energy prices. Rebound is closely linked to declining market prices. To our knowledge, our analysis is the first to apply this approach to the manufacturing industry. Finally, (iii) we suggest that the rebound effect from energy efficiency improvement should be studied in a broader perspective than is usually done. More efficient use of energy can be due to both technological development and improving technical efficiency. The latter suggested by Orea et al. (2015) and Amjadi et al. (2017). The overall effect of technological development and improved technical efficiency can together give a different picture of the rebound effect than the picture given by these factors individually.

In general, the result indicates that the rebound effect is considerable for the Swedish energy intensive industry. Regarding electricity, efficiency improvements will actually trigger an increase in the electricity consumption. Hence, the results indicate backfire. The fossil fuel rebound is found to be smaller but still substantial, with up to 80 percent of fossil fuel efficiency improvement being offset. This implies that policies that encourage an increase in energy efficiency should be combined with a raise in energy taxes.

The rest of the paper is organized as follows. In the next section the rebound effect is defined, and the literature on the subject is reviewed. In Section 3 the factor demand model is outlined theoretically and empirically. Theoretically the model is based on profit maximizing firms.

Empirically the profit function is specified as a quadratic function in a system with input demand functions. The latter includes modeling asymmetric energy prices. Lastly, substitution elasticities are specified. Data is presented in Section 4, and in Section 5 the results are provided. Section 6 concludes the paper with a discussion and some specific conclusions.

2. Defining rebound and reviewing literature

2.1 The rebound effect

Greening et al. (2000) used a four-part typology to address the mechanisms that the rebound effect can be linked to: (i) direct effects; (ii) secondary (or indirect) effects; (iii) economy-wide effects; and (iv) transformational effects. Frequently discussed in subsequent studies are the three first mechanisms (Orea et al., 2015). In this particular paper we focus on the direct rebound effect.[5]

The *direct rebound effect* refers to the microeconomic level. Efficiency improvement lowers the amount of energy required to provide an energy service, which will lower the effective price of that service. The firm responds to the lower effective price by increasing the use of the energy service and decreasing the use of other input services. This is the *substitution effect* of the direct rebound (Sorrell, 2014). See Figure 1.

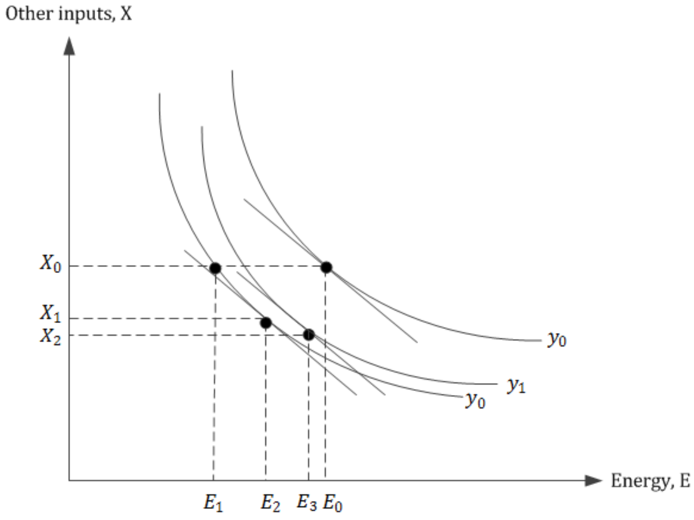

Figure 1. Energy-augmenting technological change; the substitution and output rebound effect

Source: Berkhout et al. (2000).[6]

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[5] A discussion of indirect and economy-wide effects can be found in, e.g., Greening et al. (2000), Bentzen (2004), Jenkins et al. (2011), Sorrell (2014), Sorrell and Dimitropoulos (2008).

[6] See also Sorrell (2014).

A firm uses energy, E, and other inputs, X, to produce a given level of output, Y^0. Other inputs are assumed to be separable from the energy input. This enables grouping all other inputs but energy into one nested input factor (Sorrell, 2014). Initially the firm uses the optimal mix of energy and other inputs (E_0, X_0). Assume then an energy-augmenting technological improvement, which can be seen as a pure energy productivity increase keeping the productivity of all other input factors unchanged. The energy productivity increase is reflected by a shift in the isoquant to the left. Keeping other inputs at the initial level, X_0, the potential (engineering) energy-savings then corresponds to the distance $E_0 - E_1$. However, given fixed prices, the firm will adjust to the new optimal input mix (E_2, X_1), i.e., substitute energy for other inputs to minimize the production cost. Therefore, the actual energy-savings, $E_0 - E_2$, are less than the potential savings. The size of the substitution effect is $(E_2 - E_1)$, and depends upon the curvature of the isoquant, i.e., the ease of substitution between energy and other inputs (Sorrell, 2014).

Furthermore, since technology shift lowers the unit cost of production, it creates space for the producer to reduce the output price. The price reduction increases the demand for the output and the producer increase output, from Y^0 to Y^1 in Figure 1. The producer will therefore have further needs for energy input services in production. This is the *output effect* of the direct rebound (Berkhout et al. 2000). The size of the output effect is $E_3 - E_2$, and depends on the price elasticity of demand for the output. The more elastic the demand is the larger will be the output effect of the direct rebound (Berkhout et al., 2000).[7] The substitution effect, which is estimated in this paper, is then $(E_2 - E_1)/(E_0 - E_1)$.

2.2 Literature

The literature on the rebound effect has been growing the last decades (Turner, 2013), see for example Sorrell (2007), Maxwell et al. (2011), and Jenkins et al. (2011). Considering direct, indirect, and economy-wide effects, all of these reviews reveal evidence of significant rebound, and address that this needs to be accounted for when policy targets for energy efficiency are set. This conclusion is also to be found in other recent literature. However, Jenkins et al. (2011) conclude that price-induced efficiency improvements, e.g., induced by taxes, should not be considered as a source of significant rebound effects. The specific policy implication is then to keep the effective price on energy services constant, which basically means

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[7] Saunders (2013) found that the substitution component of the direct rebound effect outweighs the output component significantly. Analyzing 30 sectors in the US, he found that the substitution component contributed to around 80 to 95 percent on average to the rebound effect. Lin and Li (2014) focus solely on the substitution component, referring to Saunders and arguing that it is usually much larger than the output one.

that any net energy productivity gains induced from these taxes are eliminated. Vivanco et al. (2016) add to this discussion by arguing that there is no single optimal policy instrument, and that policy mixes are instead to be applied. The most effective policies, however, emerge to be appropriately designed economy-wide cap-and-trade systems, and also energy and carbon taxes.

The existence of a rebound effect is widely accepted, but the magnitude is debated (Chakravarty, 2013). For instance, Howarth (1997) concludes from a restrictive theoretical model that increased energy efficiency does not necessarily lead to increased demand for energy services in the long run. Schipper and Grubb (2000) find no empirical evidence of a substantial economy-wide rebound effect within a variety of IEA countries during the 70ies and 80ies. Adetutu et al. (2016) estimate economy-wide effects for 55 countries and find that a 100 percent energy efficiency improvement leads to a 90 percent rebound effect in the short run. However, the results imply that the energy consumption will decrease by 136 percent in the long run.

It is obvious that the existing studies addressing economy-wide rebound effects show a variety of results. For further overview of the economy-wide effect literature, see, e.g., Dimitropoulos (2007), Allan et al. (2009), and Broberg et al. (2015).

Empirical studies that concern the direct rebound effect in the manufacturing industry are much scarcer than rebound studies on end-use consumer energy services (Jenkins et al., 2011). Grepperud and Rasmussen (2004) use an econometric computable general equilibrium (CGE) model to apply a macro-economic analysis of the rebound effect at the sector level in Norway. They find a significant rebound in manufacturing compared with other sectors. Saunders (2013) use a Translog unit cost function approach to estimate the rebound effect for the producing part of the US economy. The results indicate that the magnitude of the rebound were substantial during 1981-2000.

A recently arisen part of the literature, originating from Orea et al. (2015), bases its analyses on the Stochastic Frontier Analysis (SFA) approach.[8] Inspired by Orea et al. (2015), who measure the rebound effect in US residential energy consumption, Amjadi et al. (2017) is the first study using this approach to estimate the rebound effect based on data from the energy intensive industry. In this case the rebound effect is determined by the technical inefficiency component of the stochastic part of the firms' energy demand frontier, which is derived from

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[8] For an introduction to the SFA approach see, e.g., Kumbhakar and Lovell (2000).

the minimized short-run cost function. Hence, the energy demand frontier is a reflection of the technological frontier. In turn, technical inefficiency reflects deviation from the technological frontier, meaning that energy input used per unit produced output could be lowered by approaching that frontier. Since this will lower the relative price of energy services used in production a rebound effect may occur (μ in Equation 6 increases). Using this approach the substitution rebound effect is *directly* estimated from marginally improving technical energy efficiency.

Amjadi et al. (2017) find significant rebound effects from energy technical efficiency improvements regarding both fuel and electricity input in the Swedish energy intensive sectors, Iron and steel, Pulp and paper, Chemical, and Mining during 2000-2008. The average rebound effects for these sectors are 54, 31, 42, and 50 percent, respectively. The corresponding percentages for electricity are 79, 26, 75, and 37 percent, respectively. Note that these results refer to partial rebound effects, i.e., the model approach do not allow for 100 percent rebound effects or larger, and neither non-positive rebound effects.[9] Hence, energy technical efficiency improvement must give rise to rebounds, but not to full rebounds.

There are a few studies that estimate direct rebound effects in manufacturing industries by using different types of factor demand models. Referring to the SFA approach used by Amjadi et al. (2017), this means that firms are assumed to operate technically efficiently on the technological frontier. Hence, in this case, the direct rebound effect occurs due to technological development and is *indirectly* estimated from the own-price elasticity of energy (Equation 6 shows the relationship between technological development and the market price of energy). The two separate approaches, the SFA model and the factor demand model, generally complement each other by addressing two distinct aspects of increased energy productivity, i.e., technical energy efficiency and energy-augmenting technological development.

Applying a factor demand model and using time series data, Bentzen (2004) estimates the sector level rebound effect in US manufacturing during 1949-1999, by applying a translog cost function approach. The rebound is found to be approximately 48 percent. Applying the same approach on the heavy industry in China 1980 to 2011, Lin and Li (2014) found the rebound to be 4 percent. However, both studies also estimate the rebound effect under asymmetric energy price response (Gately, 1993; Gately and Huntington, 2002). In this case the elasticity of only lowering energy price indicates the magnitude of the rebound. Bentzen

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[9] Full rebound and backfire are assumed away, as well as zero rebound and super-conservation. The latter is problematic to explain from an economic point of view.

(2004) and Lin and Li (2014) found the rebound effect to be 24 and 74 percent, respectively. This indicates a larger substitutability of inputs in the Chinese industry. Using panel data, Brännlund and Lundgren (2007) estimate a quadratic profit function factor demand model for the Swedish energy incentive industry 1990-2001. The own-price elasticities for composite fuel (consisting of all fuels used, approximately 70-80 percent fossil fuel) and electricity are found to be 72 and 97 percent, respectively. This indicates a considerable rebound effect for fuel-augmenting technological growth, and almost a full rebound for electricity.

3. The factor demand model

The model used to derive the substitution rebound effect illustrated in Figure 1 is based on the assumption that firms maximize profits in a perfectly competitive environment. This implies that, taking input and output prices as given, the firm chooses an output and input levels to maximize profits.

3.1 Theory

Formally, the firm is assumed to use a variable input vector $x = [x_1, \dots, x_N]$ to produce a single output q. The price vector corresponding to inputs is denoted $w = [w_1, \dots, w_N]$, and the output price is denoted p. Then, the profit function for a representative firm may be expressed as:

$$\pi = p \cdot q^* - w' \cdot x^* = \pi(w, p) \tag{1}$$

where q^* and x^* denotes profit maximizing choices of output and variable input quantities, respectively. The profit function exhibits the standard properties of being convex in prices, i.e., non-decreasing in p and non-increasing in w, and homogenous of degree 1 in prices.

The firm's output supply and variable input demand as functions of prices are derived by applying Hotelling's lemma to Equation (1), i.e.:

$$\frac{\partial \pi(w,p)}{\partial p} = q^*(p^+, w^-) \tag{2}$$

and

$$\nabla_w[\pi(w,p)] = -x^*\left(w^{-?}, p^+\right), \tag{3}$$

respectively. The firm increases both supply and demand if the output price, p, increases. If the price of an input factor, w_n, increases the firm reduces its supply. The firm also reduces its demand for the input factor whose price rises (the own-price effect). However, whether the demand for an input factor decreases or increases when the price of another input factor increases will depend on whether inputs are gross substitutes or gross complements in production (the cross-price effect).[10] If inputs are complements the demand for the input factor decreases, and if they are substitutes the demand increases. Whether inputs are substitutes or complements in production is an empirical question (hence the "?" in the Equation 3).

In empirical analyses, the model may be estimated as a system of equations (1)-(3). The model is to be viewed as a long-run model.

3.2 Empirical model

For empirical purposes, the profit function in Equation (1) needs to be given a functional form. We follow Brännlund and Lundgren (2007) and adopt a quadratic profit function, which is a second-order approximation of an arbitrary function.[11] This is a flexible functional form that does not put any a priori restrictions on the input elasticities to be estimated.

The property of linear homogeneity of degree 1 in prices can be imposed by dividing through both sides of Equation (1) with the output price, i.e., $\pi/p = \pi(w/p)$. Then, for firm s in period t, the functional form of the normalized quadratic profit function may be expressed as (p suppressed):

$$\pi^{st} = \alpha_0 + \sum_i \alpha_i w_i^{st} + \alpha_t t + \frac{1}{2}\sum_i \sum_j \alpha_{ij} w_i^{st} w_j^{st} + \sum_i \alpha_{it} w_i^{st} t + \frac{1}{2}\alpha_{tt} t^2 + \beta_s \qquad (4)$$

$i, j = E, F, B, K, L$

Where E denotes electricity, F fossil fuels, B biofuels, K capital, and L labor. Total factor productivity is modelled by including a trend, t, which captures Hicks neutral technological change.

The expression in Equation (4) also accounts for the possibility that firms may operate under different circumstances, i.e., firm specific effects, β_s, $s = 1, \dots, S-1$. Finally, the expression satisfies symmetry, i.e., $\alpha_{ij} = \alpha_{ji}$, and $\alpha_{it} = \alpha_{ti}$.

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[10] Regarding “gross” substitutes/complements, see Chambers (1988, p. 136-137 and p. 172-174).

[11] For a discussion about the choice of functional form when the estimation of substitution elasticities is based on cost minimization, e.g., see Saunders (2008).

Applying Hotelling's lemma to Equation (4) gives the variable input demand functions corresponding to Equation (3) as follows:[12]

$$x_i^{st} = -\left[\alpha_i + \sum_j \alpha_{ij} w_j^{st} + \alpha_{it} t\right] \qquad (5)$$

By adding a stochastic component to the expressions in (4) and (5), they form a system of six equations that can be econometrically estimated with a Seemingly Unrelated Regression (SUR) approach.

3.2.1 ASYMMETRIC PRICE RESPONSE

Asymmetric price response means that firms respond more strongly to energy price increases than to energy price decreases. For instance, as a response to rising energy prices, firms increase energy efficiency by improving the energy consuming properties of the production process. However, it is unlikely that these properties are abandoned when the energy prices return to a lower level. This is a hysteresis phenomenon that should be allowed for when modeling the rebound effect (Frondel and Vance, 2013).

The rebound effect from increased energy efficiency arises due to the effective energy price, i.e., the unit cost of running the energy-consuming production process, decreases compared to market price of energy. Then, to account for asymmetric price response, when estimating the rebound effect, first consider the following expression (see, e.g., Sorrell and Dimitropoulos, 2008; Berkhout et al., 2000):

$$w_{i,eff} = \frac{w_i}{\mu} \qquad i = E, F, B \qquad (6)$$

where $w_{i,eff}$ denotes the effective energy price, w_i the market price of energy, and where μ is a component that reflects energy efficiency. When efficiency increases, i.e., $\Delta\mu > 0$, ceteris paribus, the effective price becomes lower compared to the market price, since $\Delta w_{i,eff} < 0$ and w_i unchanged (Sorrell and Dimitropoulos, 2008). Therefore, the unit cost of the energy service decreases which opens up for increased energy use in production. When the market price decline, $\Delta w_i < 0$, holding efficiency constant, a proportional decline, $1/\mu$, occurs in effective price. Again, the unit cost of the energy service decreases, which shows that rebound

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[12] In the empirical model we exclude the supply function.

is more closely related to lowered energy market prices than to increased prices. Therefore, the rebound effect can be evaluated based on the own-price elasticity and the elasticities of substitution between energy and other inputs, calculated from declining energy market prices (Bentzen, 2004; Frondel and Vance, 2013; Lin and Li, 2014).

The empirical results in Bentzen (2004) and Lin and Li (2014) indicate that the rebound effect may be considerably biased if not accounting for asymmetric price response. However, the results are based on a price decomposition approach suggested by Gately (1993) and Gately and Huntington (2002), which suffers from a couple of weaknesses (Griffin and Schulman, 2005, Frondel and Vance, 2013). Frondel and Vance (2013) argue for an alternative dummy-variable approach to overcome these weaknesses. Specifically, the market price of energy, w_i^{st}, $i = E, F, B$, is decomposed into the sum of rising, w_i^{+st}, and falling, w_i^{-st}, energy prices, where $w_i^{-st} = w_i^{st}$ if $w_i^{st} < w_i^{s,t-1}$, and $w_i^{-st} = 0$ otherwise. Hence, if $w_i^{st} \geq w_i^{s,t-1}$ then $w_i^{+st} = w_i^{st}$.

The energy demand functions in (5) are corrected to include the energy price decomposition as follows. For $i = E, F, B$:

$$x_i^{st} = -\left[\alpha_i + (\alpha_{0ii}{}^{+}D^{+st} + \alpha_{ii}^{+}D^{+st} \cdot w_i^{st} + \alpha_{ii}^{-}D^{-st} \cdot w_i^{st}) + \textstyle\sum_j \alpha_{ij} w_j^{st} + \alpha_{it} t\right] \quad (7)$$

$$j = E, F, B, K, L$$

where a dummy $D^{-st} = 1$ if $w_i^{st} < w_i^{s,t-1}$, $i = E, F, B$, and $D^{-st} = 0$ otherwise. Similarly, if $w_i^{st} \geq w_i^{s,t-1}$ then another dummy $D^{+st} = 1$ and $D^{+st} = 0$ otherwise. This means that $D^{+st} = 1 - D^{-st}$. The price decomposition is also included for $i = E, F, B$ in the profit function (4), as shown in Appendix A and Equation (A8).

For $i = K, L$

$$x_i^{st} = -\left[\alpha_i + \textstyle\sum_j \alpha_{ij} w_j^{st} + \alpha_{it} t\right], \qquad j = E, F, B, K, L \qquad (5')$$

The system of equations in (4) and (5) is typically employed when estimating the rebound effect using factor demand models. The system of equations in (4), (5’) and (7) allows for price asymmetric responses in energy consumption, which, however, does not necessarily mean that it does occur in reality. Whether this is the case requires testing the null-hypothesis empirically:

$$H_0: \alpha_{ii}^{-} = \alpha_{ii}^{+}, \qquad i = E, F, B \tag{8}$$

If the null-hypothesis cannot be rejected then there is no price asymmetric response that can cause the system of equations in (4) and (5) to result in biased estimates of the rebound effect.

The factor demand model outlined above in general terms is specified more in detail in Appendix A.

3.2.2 ELASTICITIES OF SUBSTITUTION

When the system of equations is estimated we have all the necessary estimates of responses, $\hat{\alpha}$, to obtain the elasticities of substitution. All elasticities are calculated at mean of prices and quantities, and can be assumed to apply to a fictitious firm that is representative of the data on which the analysis is based.

First, the variable input factor demand elasticities are calculated as follows:

$$\varepsilon_{ij} = -\hat{\alpha}_{ij} \cdot \frac{w_j}{x_i}, \qquad i,j = E, F, B, K, L \tag{9}$$

where $i = j$ refers to own-price elasticities that show the substitution rebound effects for $i,j = E, F, B$, and described as $(E_3 - E_1)/(E_0 - E_1)$ in Figure 1. Furthermore $i \neq j$ refers to cross price elasticities. In the case of asymmetric energy prices the own price elasticity for energy is calculated at mean of w_i^{+st} $(= D^{+st} w_i^{st})$ and w_i^{-st} $(= D^{-st} w_i^{st})$, by using $\hat{\alpha}_{ii}^{+}$ and $\hat{\alpha}_{ii}^{-}$ with $i = E, F, B$.

The supply elasticities with respect to input prices are then obtained according to:

$$\varepsilon_{iP} = -\sum_{j=1} \varepsilon_{ij}, \tag{10}$$

and

$$\varepsilon_{Pi} = -\varepsilon_{iP} \cdot w_i \frac{x_i}{q}, \tag{11}$$

Finally, the own price supply elasticity, indicating how much firms adapt the supply to a change in the market price of the produced product, is expressed as follows:

$$\varepsilon_{PP} = -\sum_{i=1} \varepsilon_{Pi}, \tag{12}$$

4. Data

The data is provided from Statistics Sweden. It includes firms with at least nine employees that are classified according to the SNI 2007 industry code. In the present paper focus is on four major energy-intensive industries; pulp and paper, iron and steel, chemical, and mining, see Table 1. These industries account for more than three quarters of the total energy use in the Swedish industrial sector.[13]

Table 1 Energy intensive manufacturing sectors (classified according to SNI2007 industry code)

SNI-code	Manufacturing Sectors	Share of energy use in industrial sector(%)
17	Pulp and paper	51
24	Iron and steel	16*
19+20+21	Chemical	9
7+8	Mining	4

*The share of 16 percent includes the metal industry (SNI25). Our study solely focuses on basic iron and steel – hence exclude the metal industry.

The data set is a firm level unbalanced panel covering the years 2001 to 2012. It includes firm specific data on sales, labor and energy expenditures, as well as the number of employees and energy quantities purchased. Firm specific energy and labor prices were calculated from the ratio of these expenditures to quantities.[14] In addition, Statistics Sweden´s industry statistics provided data on firm specific capital gross investments, which enabled us to create a firm specific capital stock by applying the perpetual inventory method (Berndt, 1991).[15]Statistics Sweden also provided data on an investment good price index, and a long term interest rate at the national level, and a sector specific producer price index (the output price), which is used to calculate the price of capital as well as the user cost of capital.[16]

For all industry sectors, except pulp and paper, electricity and non-fossil fuels are aggregated into a single variable. This is done due to computational issues, e.g., convergence problems. The non-fossil fuel category comprises for example wood fuel, solid biofuels, district heating, and waste whilst fossil fuel includes, e.g., coal, coke, gasoline, natural gas, and fuel oil.

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[13] http://www.energimyndigheten.se/statistik/industri-och-naring/?currentTab=1#mainheading

[14] Aggregate industry data present real prices (during the time period) of up to approximately 2 000 TSEK/GWh. We tolerate somewhat higher firm specific prices, by setting the upper limit at 2 500 TSEK. Prices beyond this level are seen as unrealistic and are excluded.

[15] That is: $K_t = I_t + (1-\delta)K_{t-1}$, where K_t denotes capital at time t, I_t gross investments in inventories and machinery, and δ the depreciation rate. The latter is set to 8.7 percent following King and Fullerton (1984) and Bergman (1996). To create the capital stock for the first year of data, K_t , $t = 2001$, it is assumed that $K_t = K_{t-1}$. Consequently, $K_t = I_t/\delta$.

[16] The price of capital: $w_K = P_I/P_Q * (r+\delta)$, where P_I and P_Q denote the investment good price index and the output price (sector specific producer price index), respectively, r denotes the long term market capital interest rate, and δ the 8.7 percent depreciation rate.

Descriptive statistics on the variables included in the factor demand model is provided in Table 2 to 5 for each of the sectors.

Table 2 Descriptive statistics (prices in 2005 SEK): Pulp and paper

Variable	Mean	Std.dev.
Price of electricity (TSEK/GWh), w_E	463.34	202.65
Price of non-fossil fuel (TSEK/GWh), w_B	160.21	227.25
Price of fossil fuel (TSEK/GWh), w_F	340.04	323.81
Price of capital (0-100 index), w_K	11.92	1.20
Wage (TSEK/employee), w_L	461.49	78.68
Electricity (GWh), E	171.47	380.63
Fossil Fuel (GWh), F	41.98	83.64
Non-fossil Fuel (GWh), B	396.47	1130.73
Capital (MSEK), K	479.82	911.78
Labor (number of employees), L	299	389
Output (TSEK), q	884270	1368409
Number of observations	887	

Table 3 Descriptive statistics (prices in 2005 SEK): Iron and steel

Variable	Mean	Std.dev.
Price of electricity (TSEK/GWh)	435.84	122.04
Price of electricity and non-fossil fuel (TSEK/GWh), w_E	430.67	117.97
Price of fossil fuel (TSEK/GWh), w_F	441.05	280.05
Price of capital (0-100 index), w_K	11.67	3.80
Wage (TSEK/employee), w_L	440.21	110.64
Electricity (GWh)	82.28	169.12
Electricity and bio (GWh), E	101.06	201.32
Fossil Fuel (GWh), F	442.15	2183.62
Capital (MSEK), K	498.74	1068.63
Labor (number of employees), L	460	773
Output (TSEK), q	1443835	2745384
Number of observations	418	

Table 4 Descriptive statistics (prices in 2005 SEK): Chemical

Variable	Mean	Std.dev.
Price of electricity (TSEK/GWh)	483.24	183.55
Price of electricity and non-fossil fuel (TSEK/GWh), w_E	457.61	176.99
Price of fossil fuel (TSEK/GWh), w_F	365.47	355.61
Price of capital (0-100 index), w_K	12.33	1.83
Wage (TSEK/employee), w_L	530.04	206.00
Electricity (GWh)	35.65	114.44
Electricity and bio (GWh), E	50.98	133.44
Fossil Fuel (GWh), F	80.54	621.18
Capital (MSEK), K	511.1	1610.0
Labor (number of employees), L	279	1054
Output (TSEK), q	1337634	6022973
Number of observations	1065	

Table 5 Descriptive statistics (prices in 2005 SEK): Mining

Variable	Mean	Std.dev.
Price of electricity (TSEK/GWh)	602.92	307.16
Price of electricity and non-fossil fuel (TSEK/GWh), w_E	588.83	304.03
Price of fossil fuel (TSEK/GWh), w_F	608.52	522.19
Price of capital (0-100 index), w_K	11.64	2.64
Wage (TSEK/employee), w_L	432.97	100.95
Electricity (GWh)	65.91	286.43
Electricity and bio (GWh), E	83.03	350.69
Fossil Fuel (GWh), F	60.50	263.77
Capital (MSEK), K	599.87	2077.91
Labor (number of employees), L	176	592
Output (TSEK), q	551357	2345500
Number of observations	372	

Typically, large energy industry consumers operate in capital-intensive industries with energy-intensive processes. In a statistical report, provided by Statistics Sweden and the Swedish Energy Agency, firms are categorized based on their annual consumption of electricity. According to this, the largest industry consumers are those that use more than 70 GWh a year. [17] In our data set, the pulp and paper and iron and steel industry belong to this category with an average consumption of 171 and 82 GWh, respectively.

The statistical report from Statistics Sweden and the Swedish Energy Agency also indicate that these large consumers will meet the lowest electricity price (in 2007 SEK); ranging from

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[17] https://www.scb.se/Statistik/EN/EN0304/2014K02/EN0304_2014K02_SM_EN24SM1403.pdf.

420 TSEK to 480 TSEK/GWh in 2012. The electricity price peaked at 640 TSEK/GWh in 2010 (January to June). In our data, the average electricity price is 463, 436, and 483 TSEK/GWh for the pulp and paper, iron and steel, and chemical industry, respectively (prices in 2005 SEK). The mining industry differs from the others with a relatively high price of 603 TSEK/GWh. Hence the data indicate that a sector that consumes more electricity is not necessarily the one that will meet the lowest price of electricity.

By far the largest user of fossil fuel is the iron and steel industry, consuming on average 442 GWh, whereas the pulp and paper industry is by far the smallest consumer, using on average 42 GWh. Again data shows that the largest consumer does not necessarily meet the lowest price. The average price is 441 and 340 TSEK/GWh in the iron and steel and pulp and paper industry, respectively.

Even though the pulp and paper industry is the largest consumer of electricity in absolute terms, its main energy source is non-fossils (65 percent).[18] In contrast, the main energy source in the iron and steel, chemical, and mining sector is fossil fuel (81 percent), fossil fuel (61 percent), and electricity (46 percent), respectively. In mining, however, the fossil fuel share and the electricity share is almost equal.

Finally, the most electric intensive industries, measured as the ratio of electricity consumed to the output produced, are the pulp and paper and mining industries. In addition, the absolute level of electricity consumption is relatively high for the pulp and paper sector. Mansikkasalo and Söderholm (2013) show that these are factors determining if a firm is to participate in voluntary energy efficiency improvement programs or not.

5. Results

As established in Section 2, Figure 1, the size of the direct rebound effect depends on a substitution effect and an output effect. In this paper the substitution effect is estimated, and in this section the results from the empirical analyses are presented.

5.1 Input cost shares and energy intensity

Table 10 illustrates the average cost shares of each input factor in each sector in relation to total production costs; electricity (s_E), non-fossil fuel (s_B), fossil fuel (s_F), capital (s_C), and

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[18] $i/E+B+F, i=E,B,F.$

labor (s_L).[19] However, for all sectors except pulp and paper electricity and non-fossil fuel are aggregated into one energy variable.

The labor cost share dominates and amounts to 70 percent or slightly less in all sectors except in mining, where the share is much lower (53 percent). Capital also accounts for a relatively high cost share. The mining industry appears to be relatively capital intensive compared to the other sectors. In contrast, the iron and steel industry appears to be the opposite. The total energy share is fairly small. In chemicals and mining it is 10 and 13 percent respectively. In both iron and steel and pulp and paper the corresponding share is 17 percent.

Table 10 Input factor cost shares (Std. Dev. within parentheses)

Input factors	Pulp and paper	Iron and steel	Chemical	Mining
Electricity (s_E)	0.10 (0.12)	-	-	-
Energy* (s_E)		0.10 (0.08)	0.07 (0.08)	0.05 (0.07)
Non-fossil fuel (s_B)	0.04 (0.08)	-	-	-
Fossil fuel (s_F)	0.03 (0.05)	0.07 (0.09)	0.03 (0.07)	0.08 (0.11)
Capital (s_C)	0.16 (0.11)	0.14 (0.09)	0.20 (0.14)	0.34 (0.17)
Labor (s_L)	0.67 (0.21)	0.69 (0.15)	0.70 (0.18)	0.53 (0.17)

*Electricity + non-fossil fuel

Table 11 provides the average energy intensity in each sector, i.e., the ratio of energy input (MWh) used in production in relation to produced output (the latter is measured as firm specific sales value divided by a sector specific producer price index).

Table 11 Energy intensity in each sector (Std. Dev. within parentheses)

Pulp and paper	Iron and steel	Chemical	Mining
0.33 (0.49)	0.18 (0.33)	0.13 (0.49)	0.11 (0.13)

The energy intensity varies considerably between sectors with the pulp and paper sector being the most intensive one. This is also a sector in which the energy cost share (table 10) is relatively high (17 percent). The same pattern prevails such that a relatively low intensity corresponds to a relatively low energy cost share – as in the mining industry.

5.2 The rebound effect

Tables 12 to 15 provide own-price elasticities for different energy inputs. All own-price elasticities have the expected sign stipulated by economic theory, and the parameter estimates,

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[19] $s_i = w_i / \sum_i w_i,\ i = E, B, F, K, L.$

from which the rebound effects are calculated (see Equation 9), are all significant at the 5 percent level. Parameter estimates for each sector and full tables of own- and cross-price elasticities are provided in Appendix B and C, respectively.

As was stated in Section 3.2.1, an analysis of the rebound effect should allow for an asymmetric price response. This since the effect might be closer related to decreasing energy market prices than increasing prices (see Equation 6 and the related discussion). Tables 12 to 15 therefore present rebound effects, separating between downward and upward prices.

However, the results from the estimations reveal no significant difference in response to decreasing versus increasing prices (the confidence intervals are overlapping). This is consistent with the findings in Frondel and Vance (2013). This implies that the rebound effect could be estimated without dividing energy prices into an upward and downward component. Appendix B therefore provides parameter estimates from such a symmetric energy price response. As expected, calculating the rebound effect from these estimates generate pretty much the same result, as when incorporating asymmetry to the equation system. However, from now on our comments concern rebounds related to decreasing prices.

Table 13 Own price energy elasticities: Energy price decomposition: Pulp and paper

	Electricity	95% Conf. Intervall	Fossil fuel	95% Conf. Intervall	Non-fossil fuel	95% Conf. Intervall
Input price down	-1.32	-0.92 ($\alpha_{EE}^{-} = 0.34$) -1.73 ($\alpha_{EE}^{-} = 0.64$)	-0.24	-0.01 ($\alpha_{FF}^{-} = 0.001$) -0.40 ($\alpha_{FF}^{-} = 0.05$)	-0.40	-0.21 ($\alpha_{BB}^{-} = 0.52$) -0.58 ($\alpha_{BB}^{-} = 1.44$)
Input price up	-1.19	-0.92 ($\alpha_{EE}^{+} = 0.34$) -1.46 ($\alpha_{EE}^{+} = 0.54$)	-0.24	-0.08 ($\alpha_{FF}^{+} = 0.01$) -0.32 ($\alpha_{FF}^{+} = 0.04$)	-0.27	-0.20 ($\alpha_{BB}^{+} = 0.49$) -0.36 ($\alpha_{BB}^{+} = 0.88$)

Table 12 Own price energy elasticities: Energy price decomposition: Iron and steel

	Electricity and non-fossil fuel	95% Conf. Intervall	Fossil fuel	95% Conf. Intervall
Input price down	-1.41	-0.85 ($\alpha_{EE}^{-} = 0.20$) -1.96 ($\alpha_{EE}^{-} = 0.46$)	-0.43	-0.02 ($\alpha_{FF}^{-} = 0.02$) -0.84 ($\alpha_{FF}^{-} = 0.84$)
Input price up	-0.64	-0.26 ($\alpha_{EE}^{+} = 0.06$) -1.02 ($\alpha_{EE}^{+} = 0.24$)	-0.45	-0.15 ($\alpha_{FF}^{+} = 0.15$) -0.75 ($\alpha_{FF}^{+} = 0.75$)

Table 14 Own price energy elasticities: Energy price decomposition: Chemical

	Electricity and non-fossil fuel	95% Conf. Intervall	Fossil fuel	95% Conf. Intervall
Input price down	-1.62	-0.99 ($\alpha_{EE}^{-} = 0.11$) -2.15 ($\alpha_{EE}^{-} = 0.24$)	-2.41	-1.45 ($\alpha_{FF}^{-} = 0.32$) -3.27 ($\alpha_{FF}^{-} = 0.72$)
Input price up	-1.79	-1.43 ($\alpha_{EE}^{+} = 0.16$) -2.24 ($\alpha_{EE}^{+} = 0.25$)	-0.59	-0.14 ($\alpha_{FF}^{+} = 0.03$) -1.04 ($\alpha_{FF}^{+} = 0.23$)

Table 15 Own price energy elasticities: Energy price decomposition: Mining

	Electricity and non-fossil fuel	95% Conf. Intervall	Fossil fuel	95% Conf. Intervall
Input price down	-1.42	-0.92 ($\alpha_{EE}^{-} = 0.13$) -1.99 ($\alpha_{EE}^{-} = 0.28$)	-0.80	-0.30 ($\alpha_{FF}^{-} = 0.03$) -1.21 ($\alpha_{FF}^{-} = 0.12$)
Input price up	-1.35	-0.85 ($\alpha_{EE}^{+} = 0.12$) -1.92 ($\alpha_{EE}^{+} = 0.27$)	-0.80	-0.40 ($\alpha_{FF}^{+} = 0.04$) -1.21 ($\alpha_{FF}^{+} = 0.12$)

Typically, the results indicate that the rebound effect would be considerable, not the least for electricity. Since the demand for electricity is elastic, ranging from -1.32 in the pulp and paper industry to -1.62 in the chemical industry the results actually indicate “backfire”, i.e., electricity efficiency improvements will lead to increased electricity use. [20] However, regarding fossil fuel the demand is instead inelastic in three of the sectors, with an own-price elasticity ranging from -0.24 to -0.80. Thus the fossil fuel rebound is smaller than the one for electricity.[21] The rebound is still substantial since 24 to 80 percent of the potential fossil fuel savings due to fossil fuel efficiency improvement is lost.

Our results, showing an elastic Swedish industry energy demand, confirm the results found in a previous study using a similar model. Brännlund and Lundgren (2007) find that the own-price elasticity of electricity in iron and steel and chemical is -1.86 and -1.45, respectively. The corresponding elasticities for fuel (70 to 80 percent fossil) are -1.45 and -1.90, respectively. However, in contrast to the Brännlund and Lundgren study, our results indicate that the demand for fossil fuel is less elastic than the demand for electricity and non-fossils. One reason could be that their study covers the period 1990 to 2001 while our study focus on the period 2001-2012. Hence, policy induced changes (taking place in the last decades) may have triggered a more extensive use of electricity and non-fossils, thus making firms more sensitive to changes in electricity an non-fossil fuel prices.

6. Concluding remarks

The purpose of this paper has been to estimate the potential direct rebound effect resulting from energy efficiency improvements. The focus has been on four energy intensive sectors in Sweden during the period 2001-2012; Pulp and paper, Iron and steel, Chemical and Mining. Energy efficiency improvements lower the effective price of energy services, and hence give

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[20] In terms of the substitution effect component of the rebound, see Figure 1.

[21] This result is partly supported by the outcome in Amjadi et al. (2017). They estimate the rebound effect in the same Swedish industries for the period 2000-2008. However, they analyze a somewhat different source of the rebound effect (technical efficiency instead of technological development), and therefore are the sizes of the rebound not strictly comparable.

firms incentives to use more energy input and less of other inputs. Thus, due to a rebound effect the potential energy savings will be at least partly offset. This mechanism is widely accepted (Chakrawarty et al., 2013). Still, the magnitude of the effect is disputed.

Determining the extent of the rebound effect is difficult due to, e.g., methodological challenges. Hence applying different methodological approaches may generate quite different outcomes. In this paper we apply a factor demand model to estimate energy own-price elasticities, which serve as approximations (or simulations) of the magnitude of the rebound effect (the substitution effect). This approach may lead to the magnitude of the rebound being overestimated (Sorrell et al., 2009). This since, e.g., energy efficiency improvements are generated exogenously and not as a response to increasing energy prices (see Equation 6 and related discussion).

Still, our results confirm a common consensus on the existence of the rebound effect. In terms of electricity and non-fossil fuels, efficiency improvements could even result in ‘backfire’. This whilst the potential for a large rebound effect is less when it comes to fossil fuel. In line with our results, Amjadi et al. (2017) also find the rebound effect in the Swedish energy intensive industries to be significant. They use a Stochastic Frontier Analysis (SFA) approach to estimate the potential rebound due to a more efficient use of energy input, given technology (improved technical efficiency). This approach does not allow for ‘backfire’ and, therefore, it cannot be excluded that it occasionally may underestimate the rebound effect.

Due to methodological differences our study and the Amjadi et al. (2017) study does not generate comparable results; but we argue that the results could be seen as complementary. Our analysis is based on a factor demand model, and the rebound is interpreted as a result from technological change, and not technical efficiency change. Hence, the total rebound effect can actually be divided into two components, i.e., technological change and technical efficiency change. This separation of the total effect follows the same principle as when dividing a productivity change into these two components (see the literature of productive efficiency, e.g., Grosskopf, 2003).

The results in this study, together with the results in, e.g., Amjadi et al. (2017) and Brännlund and Lundgren (2007), indicate that energy efficiency improvements in the Swedish energy intensive industry have significant rebound effects. This should have consequences for the shaping of policies that aim to reduce energy consumption, such as voluntary industry energy efficiency programs.

6.1 Policy implications

The European Commission has declared that the most efficient energy is the one which is not consumed. Such an ambition states the importance of not implementing measures resulting in rebound effects.

In January 2017, the Swedish government suggested reimplementation of a voluntary program corresponding to the phased out so called PFE program, which targeted energy-intensive industries (Government Bill 2017:2). The basic idea of PFE was that firms that participated in the program, and committed to energy efficiency investments, was exempted from energy taxation. Our results, together with the results in a large body of literature, can be interpreted as if this policy design is not a good idea.

If programs of this type actually lead to considerable energy efficiency improvements that otherwise would not have had occurred, the results indicate that the substantial part of the potential energy savings would be lost due to the rebound effect. It cannot even be excluded that most of the potential energy saving is lost. The reason is the resulting lower price of energy services. This shows the importance of not tax-exempting firms that participate in voluntary programs, but instead raise energy taxes in order to keep the balance between the price of energy services and market energy prices – this if the political aim is to actually reduce energy consumption in society. Tax exemption will actually increase the rebound effect.

Voluntary energy efficiency programs, similar to the earlier PFE-program in Sweden, should be combined with energy taxation policies - if the aim is to reduce energy use. However, one can then question the purpose of implementing such programs in the first place. It would be more straightforward and cost-effective to focus directly on raising energy taxes.

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Appendix A

Decomposition of energy price

The decomposition of market energy prices follows Frondel and Vance (2013). Let w_i^{st} be the observed market price for energy, $i = E, F, B$ (electricity, fossil fuel and biofuel).

The market price is decomposed into rising, w_i^{+st}, and falling, w_i^{-st}, energy prices as:

$$w_i^{st} = w_i^{+st} + w_i^{-st}, \qquad i = e = E, F, B \tag{A1}$$

where $w_i^{+st} = w_i^{st}$ if $w_i^{st} \geq w_i^{s,t-1}$, $w_i^{+st} = 0$ otherwise, and where $w_i^{-st} = w_i^{st}$ if $w_i^{st} < w_i^{s,t-1}$, $w_i^{-st} = 0$ otherwise.

In the empirical estimations a dummy-variable-approach is used to decompose the market energy prices. That is, when $w_i^{st} \geq w_i^{s,t-1}$ then $D^{+st} = 1$, and zero otherwise. When $w_i^{st} < w_i^{s,t-1}$ then $D^{-st} = 1$, and zero otherwise. Hence, $D^{+st} = 1 - D^{-st}$.

A numerical example of the price decomposition approach suggested by Frondel and Vance (2013), $e = E, F, B$.

s	**t**	$\boldsymbol{w_e^{st}}$	$\boldsymbol{w_e^{+st}}$	$\boldsymbol{w_e^{-st}}$	$\boldsymbol{D^{+st}}$	$\boldsymbol{D^{-st}}$	$\boldsymbol{D^{+st}w_e^{st}}$	$\boldsymbol{D^{-st}w_e^{st}}$
1	1	1	1	0	1	0	1	0
1	2	2	2	0	1	0	2	0
1	3	3	3	0	1	0	3	0
1	4	3	3	0	1	0	3	0
1	5	2	0	2	0	1	0	2
1	6	3	3	0	1	0	3	0
1	7	2	0	2	0	1	0	2
1	8	1	0	1	0	1	0	1

The factor demand model

SYMMETRIC ENERGY PRICE RESPONSE

The normalized quadratic profit function (p suppressed):

$$\pi^{st} = \alpha_0 + \alpha_E w_E^{st} + \alpha_F w_F^{st} + \alpha_B w_B^{st} + \alpha_K w_K^{st} + \alpha_L w_L^{st} + \alpha_t t$$

$$+\frac{1}{2}\alpha_{EE}(w_E^{st})^2 + \alpha_{EF} w_E^{st} w_F^{st} + \alpha_{EB} w_E^{st} w_B^{st} + \alpha_{EK} w_E^{st} w_K^{st} + \alpha_{EL} w_E^{st} w_L^{st} + \alpha_{Et} w_E^{st} t$$

$$+\frac{1}{2}\alpha_{FF}(w_F^{st})^2 + \alpha_{FB} w_F^{st} w_B^{st} + \alpha_{FK} w_F^{st} w_K^{st} + \alpha_{FL} w_F^{st} w_L^{st} + \alpha_{Ft} w_F^{st} t$$

$$+\frac{1}{2}\alpha_{BB}(w_B^{st})^2 + \alpha_{BK} w_B^{st} w_K^{st} + \alpha_{BL} w_B^{st} w_L^{st} + \alpha_{Bt} w_B^{st} t$$

$$+\frac{1}{2}\alpha_{KK}(w_K^{st})^2 + \alpha_{KL} w_K^{st} w_L^{st} + \alpha_{Kt} w_K^{st} t$$

$$+\frac{1}{2}\alpha_{LL}(w_L^{st})^2 + \alpha_{Lt} w_L^{st} t$$

$$+\frac{1}{2}\alpha_{tt} t^2 + \beta_s \qquad \text{(A2)}$$

The input demand functions:

$$E^{st} = -[\alpha_E + \alpha_{EE} w_E^{st} + \alpha_{EF} w_F^{st} + \alpha_{EB} w_B^{st} + \alpha_{EK} w_K^{st} + \alpha_{EL} w_L^{st} + \alpha_{Et} t] \qquad \text{(A3)}$$

$$F^{st} = -[\alpha_F + \alpha_{EF} w_E^{st} + \alpha_{FF} w_F^{st} + \alpha_{FB} w_B^{st} + \alpha_{FK} w_K^{st} + \alpha_{FL} w_L^{st} + \alpha_{Ft} t] \qquad \text{(A4)}$$

$$B^{st} = -[\alpha_B + \alpha_{EB} w_E^{st} + \alpha_{FB} w_F^{st} + \alpha_{BB} w_B^{st} + \alpha_{BK} w_K^{st} + \alpha_{BL} w_L^{st} + \alpha_{Bt} t] \qquad \text{(A5)}$$

$$K^{st} = -[\alpha_K + \alpha_{EK} w_E^{st} + \alpha_{FK} w_F^{st} + \alpha_{BK} w_B^{st} + \alpha_{KK} w_K^{st} + \alpha_{KL} w_L^{st} + \alpha_{Kt} t] \qquad \text{(A6)}$$

$$L^{st} = -[\alpha_L + \alpha_{EL} w_E^{st} + \alpha_{FL} w_F^{st} + \alpha_{BL} w_B^{st} + \alpha_{KL} w_K^{st} + \alpha_{LL} w_L^{st} + \alpha_{Lt} t] \qquad \text{(A7)}$$

The normalized quadratic profit function:

$$\pi^{st} = \alpha_0 + \alpha_E w_E^{st} + \alpha_F w_F^{st} + \alpha_B w_B^{st} + \alpha_K w_K^{st} + \alpha_L w_L^{st} + \alpha_t t$$

$$+\frac{1}{2}(\alpha_{0EE}^{+} D^{+st} + \alpha_{EE}^{+} D^{+st} \cdot (w_E^{st})^2 + \alpha_{EE}^{-} D^{-st} \cdot (w_E^{st})^2) + \alpha_{EF} w_E^{st} w_F^{st} + \alpha_{EB} w_E^{st} w_B^{st} +$$

$$\alpha_{EK} w_E^{st} w_K^{st} + \alpha_{EL} w_E^{st} w_L^{st} + \alpha_{Et} w_E^{st} t$$

$$+\frac{1}{2}(\alpha_{0FF}^{+} D^{+st} + \alpha_{FF}^{+} D^{+st} \cdot (w_F^{st})^2 + \alpha_{FF}^{-} D^{-st} \cdot (w_F^{st})^2) + \alpha_{FB} w_F^{st} w_B^{st} + \alpha_{FK} w_F^{st} w_K^{st} +$$

$$\alpha_{FL} w_F^{st} w_L^{st} + \alpha_{Ft} w_F^{st} t$$

$$+\frac{1}{2}(\alpha_{0BB}^{+} D^{+st} + \alpha_{BB}^{+} D^{+st} \cdot (w_B^{st})^2 + \alpha_{BB}^{-} D^{-st} \cdot (w_B^{st})^2) + \alpha_{BK} w_B^{st} w_K^{st} + \alpha_{BL} w_B^{st} w_L^{st} +$$

$$\alpha_{Bt} w_B^{st} t$$

$$+\frac{1}{2}\alpha_{KK}(w_K^{st})^2 + \alpha_{KL} w_K^{st} w_L^{st} + \alpha_{Kt} w_K^{st} t$$

$$+\frac{1}{2}\alpha_{LL}(w_L^{st})^2 + \alpha_{Lt} w_L^{st} t$$

$$+\frac{1}{2}\alpha_{tt} t^2 + \beta_s \tag{A8}$$

The input demand functions:

$$E^{st} = -[\alpha_E + (\alpha_{0EE}^{+} D^{+st} + \alpha_{EE}^{+} D^{+st} \cdot w_E^{st} + \alpha_{EE}^{-} D^{-st} \cdot w_E^{st}) + \alpha_{EF} w_F^{st} + \alpha_{EB} w_B^{st} +$$

$$\alpha_{EK} w_K^{st} + \alpha_{EL} w_L^{st} + \alpha_{Et} t] \tag{A9}$$

$$F^{st} = -[\alpha_F + \alpha_{EF} w_E^{st} + (\alpha_{0FF}^{+} D^{+st} + \alpha_{FF}^{+} D^{+st} \cdot w_F^{st} + \alpha_{FF}^{-} D^{-st} \cdot w_F^{st}) + \alpha_{FB} w_B^{st} +$$

$$\alpha_{FK} w_K^{st} + \alpha_{FL} w_L^{st} + \alpha_{Ft} t] \tag{A10}$$

$$B^{st} = -[\alpha_B + \alpha_{EB} w_E^{st} + \alpha_{FB} w_F^{st} + (\alpha_{0BB}^{+} D^{+st} + \alpha_{BB}^{+} D^{+st} \cdot w_B^{st} + \alpha_{BB}^{-} D^{-st} \cdot w_B^{st}) +$$

$$\alpha_{BK} w_K^{st} + \alpha_{BL} w_L^{st} + \alpha_{Bt} t] \tag{A11}$$

$$K^{st} = -[\alpha_K + \alpha_{EK} w_E^{st} + \alpha_{FK} w_F^{st} + \alpha_{BK} w_B^{st} + \alpha_{KK} w_K^{st} + \alpha_{KL} w_L^{st} + \alpha_{Kt} t] \tag{A6}$$

$$L^{st} = -[\alpha_L + \alpha_{EL} w_E^{st} + \alpha_{FL} w_F^{st} + \alpha_{BL} w_B^{st} + \alpha_{KL} w_K^{st} + \alpha_{LL} w_L^{st} + \alpha_{Lt} t] \tag{A7}$$

Appendix B: Parameter estimates

Tables B1 to B4 shows the parameter estimates for the system of equations, including the profit function.

Table B1: Pulp and paper

	Equations A2, A3-A7		Equations A8, A6-A7, A9-A11		Equations A8, A9-A11
	Coef.	**Std. Err.**	**Coef.**	**Std. Err.**	**95% Conf. Intervall**
α_0	1272.27	8156.11	1493.08	8199.44	
α_E	-514.69	48.21	-530.97	55.44	
α_{EE}	0.44	0.05			
α_{0EE}			12.72	30.68	
α_{EE}^{+}			0.44	0.05	0.34 - 0.54
α_{EE}^{-}			0.49	0.08	0.34 - 0.64
α_{EF}	0.09	0.01	0.09	0.01	
α_{EB}	0.29	0.05	0.30	0.05	
α_{EK}	0.81	0.11	0.84	0.11	
α_{EL}	0.46	0.05	0.47	0.05	
α_{Et}	-22.61	4.16	-23.31	4.24	
α_F	-110.78	12.77	-113.20	13.72	
α_{FF}	0.03	0.01			
α_{0FF}			1.80	6.85	
α_{FF}^{+}			0.03	0.01	0.01 – 0.04
α_{FF}^{-}			0.03	0.01	0.001 – 0.05
α_{FB}	0.06	0.01	0.06	0.01	
α_{FK}	0.13	0.04	0.14	0.04	
α_{FL}	0.04	0.02	0.04	0.02	
α_{Ft}	-1.33	0.93	-1.36	0.94	
α_B	-283.63	86.53	-392.83	105.33	
α_{BB}	0.62	0.09			
α_{0BB}			109.78	61.63	
α_{BB}^{+}			0.68	0.10	0.49 – 0.88
α_{BB}^{-}			0.98	0.23	0.52 - 1.44
α_{BK}	0.47	0.10	0.53	0.11	
α_{BL}	0.10	0.05	0.12	0.05	
α_{Bt}	-54.62	10.72	-55.02	10.73	
α_K	-967.36	408.43	-987.29	408.67	
α_{KK}	13.21	25.91	13.59	25.92	
α_{KL}	0.32	0.21	0.34	0.21	
α_{Kt}	-42.50	13.91	-43.37	13.94	
α_L	-568.34	68.94	-572.16	69.10	
α_{LL}	0.30	0.12	0.30	0.12	
α_{Lt}	-15.45	4.38	-15.79	4.39	
α_t	33902.62	15758.8	32839.41	15917.03	
α_{tt}	-723.75	2221.88	-495.51	2243.87	

Table B2: Iron and Steel

	Equations A2, A3-A7		Equations A8, A6-A7, A9-A11		Equations A8,A9-A11
	Coef.	**Std. Err.**	**Coef.**	**Std. Err.**	**95% Conf. Intervall**
α_0	379.93	9091.64	391.32	9111.08	
α_E	-223.24	44.54	-270.73	49.10	
α_{EE}	0.20	0.04			

α_{0EE}			70.76	32.50	
α_{EE}^{+}			0.15	0.05	0.06 – 0.24
α_{EE}^{-}			0.33	0.07	0.20 – 0.46
α_{EF}	0.10	0.02	0.10	0.02	
α_{EK}	0.07	0.24	0.07	0.24	
α_{EL}	0.001	0.06	0.002	0.06	
α_{Et}	1.34	2.40	1.05	2.40	
α_{F}	-796.28	164.14	-761.14	173.01	
α_{FF}	0.45	0.15			
α_{0FF}			-60.25	109.89	
α_{FF}^{+}			0.45	0.15	0.15 – 0.75
α_{FF}^{-}			0.43	0.21	0.02 – 0.84
α_{FK}	0.37	0.14	0.37	0.14	
α_{FL}	0.25	0.09	0.25	0.09	
α_{Ft}	31.71	13.66	30.33	13.71	
α_{K}	-502.24	371.85	-503.84	371.91	
α_{KK}	29.99	19.28	30.37	19.28	
α_{KL}	-1.13	0.40	-1.14	0.40	
α_{Kt}	6.25	24.06	5.37	24.06	
α_{L}	-695.33	165.35	-689.59	165.48	
α_{LL}	0.37	0.21	0.36	0.21	
α_{Lt}	6.62	8.49	5.53	9.24	
α_{t}	-50414.17	23800.11	-52980.59	24068.76	
α_{tt}	289.57	2726.25	791.89	2780.31	

Table B3: Chemicals

	Equations A2, A3-A7		Equations A8, A6-A7, A9-A11		Equations A8, A9-A11
	Coef.	**Std. Err.**	**Coef.**	**Std. Err.**	**95% Conf. Intervall**
α_{0}	1427.81	20458.45	1265.93	20480.08	
α_{E}	-81.44	15.67	-61.58	20.79	
α_{EE}	0.18	0.02			
α_{0EE}			-32.46	19.23	
α_{EE}^{+}			0.20	0.02	0.16 – 0.25
α_{EE}^{-}			0.18	0.03	0.11 – 0.24
α_{EF}	0.02	0.01	0.02	0.01	
α_{EK}	0.51	0.15	0.52	0.15	
α_{EL}	-0.04	0.02	-0.04	0.02	
α_{Et}	-6.70	1.33	-7.60	1.36	
α_{F}	-3.15	59.97	-197.54	73.73	
α_{FF}	0.16	0.05			
α_{0FF}			219.92	49.66	
α_{FF}^{+}			0.13	0.05	0.03 – 0.23
α_{FF}^{-}			0.53	0.11	0.32 – 0.74
α_{FK}	0.05	0.11	0.07	0.11	
α_{FL}	-0.06	0.06	-0.05	0.06	
α_{Ft}	-17.69	6.07	-16.61	6.02	
α_{K}	-461.62	504.49	-466.24	504.79	
α_{KK}	26.32	31.56	26.20	31.58	
α_{KL}	-0.45	0.15	-0.46	0.15	
α_{Kt}	-56.39	24.08	-56.31	24.09	

α_L	-174.84	90.84	-175.92	90.76	
α_{LL}	0.09	0.06	0.09	0.06	
α_{Lt}	-12.76	10.54	-12.59	10.54	
α_t	-11035.48	32059.85	-15071.04	32105.50	
α_{tt}	7692.29	4888.21	8268.55	4895.53	

Table B4: Mining

	Equations A2, A3-A7		Equations A8, A6-A7, A9-A11		Equations A8, A9-A11
	Coef.	**Std. Err.**	**Coef.**	**Std. Err.**	**95% Conf. Intervall**
α_0	-651.52	19892.82	-740.80	19900.47	
α_E	-396.47	75.35	-430.16	75.65	
α_{EE}	0.20	0.04			
α_{0EE}			7.11	9.17	
α_{EE}^{+}			0.19	0.04	0.12-0.27
α_{EE}^{-}			0.20	0.04	0.13-0.28
α_{EF}	0.10	0.03	0.10	0.03	
α_{EK}	1.16	0.23	1.17	0.23	
α_{EL}	0.36	0.06	0.37	0.06	
α_{Et}	-0.04	0.05	-0.04	0.05	
α_F	-223.72	54.99	-231.25	56.05	
α_{FF}	0.08	0.02			
α_{0FF}			10.26	14.43	
α_{FF}^{+}			0.08	0.02	0.04-0.12
α_{FF}^{-}			0.08	0.02	0.03-0.12
α_{FK}	0.39	0.15	0.39	0.15	
α_{FL}	0.16	0.04	0.16	0.04	
α_{Ft}	-0.01	0.04	-0.01	0.04	
α_K	-2683.12	524.09	-2702.62	524.06	
α_{KK}	47.37	19.36	47.99	19.36	
α_{KL}	1.46	0.45	1.47	0.44	
α_{Kt}	0.03	0.33	0.03	0.33	
α_L	-730.20	129.62	-733.48	129.59	
α_{LL}	0.61	0.12	0.62	0.12	
α_{Lt}	-0.04	0.09	-0.04	0.09	
α_t*	398.81	298.65	405.08	298.36	
α_{tt}	-0.19	0.39	-0.20	0.39	

*In order for the system to converge in case of the mining industry, the trend variable had to be rescaled from 1 to 1000, 2 to 2000 and so on. For this reason, the trend parameter value is of lesser (absolute) size, compared to the other industries.

Appendix C: Own- and cross price elasticities

PULP AND PAPER

Table C1 Own- and cross price elasticites: Pulp and paper

	s	pe	pf	pb	r	w	p
E	0.10	-1.19	-0.18	-0.27	-0.06	-1.24	2.94
F	0.03	-0.99	-0.24	-0.23	-0.04	-0.44	1.94
B	0.04	-0.34	-0.05	-0.25	-0.01	-0.12	0.77
K	0.16	-0.78	-0.09	-0.16	-0.33	-0.31	1.67
L	0.67	-0.71	-0.05	-0.05	-0.01	-0.46	1.28
Q		-0.2642	-0.0336	-0.0551	-0.0108	-0.1997	0.5634

Table C2 Own- and cross price elasticites – asymmetric energy price response: Pulp and paper

	s	pe	pf	pb	r	w	p
E	0.10	-1.32	-0.18	-0.28	-0.06	-1.26	3.10
F	0.03	-0.99	-0.24	-0.23	-0.04	-0.44	1.94
B	0.04	-0.35	-0.05	-0.40	-0.02	-0.14	0.96
K	0.16	-0.80	-0.10	-0.18	-0.34	-0.33	1.75
L	0.67	-0.73	-0.05	-0.06	-0.01	-0.46	1.31
Q	0.10	-0.2786	-0.0336	-0.0687	-0.0113	-0.2044	0.5966

IRON AND STEEL

Table C3 Own- and cross price elasticites: Iron and steel

	s	pe	pf	r	w	p
E	0.10	-0.85	-0.44	-0.01	-0.004	1.30
F	0.07	-0.10	-0.45	-0.01	-0.25	0.81
K	0.14	-0.06	-0.33	-0.70	1.00	0.09
L	0.69	-0.001	-0.24	0.03	-0.35	0.56
q		-0.0392	-0.1094	-0.0004	-0.0785	0.2275

Table C4 Own- and cross price elasticites – asymmetric energy price response: Iron and steel

	s	pe	pf	r	w	p
E	0.10	-1.41	-0.44	-0.01	-0.01	1.87
F	0.07	-0.10	-0.43	-0.01	-0.25	0.79
K	0.14	-0.06	-0.33	-0.71	1.01	0.09
L	0.69	-0.002	-0.24	0.03	-0.35	0.56
q		-0.0564	-0.1067	-0.0004	-0.0785	0.242

CHEMICALS

Table C5 Own- and cross price elasticites: Chemicals

	s	pe	pf	r	w	p
E	0.07	-1.62	-0.14	-0.12	-0.42	2.30
F	0.03	-0.11	-0.73	-0.01	0.40	0.45
K	0.20	-0.46	-0.04	-0.63	0.47	0.66
L	0.70	0.065	0.078	0.0198	-0.171	0.01
q		-0.0401	-0.0099	-0.0031	-0.0011	0.0542

Table C6 Own- and cross price elasticites – asymmetric energy price response: Chemicals

	s	pe	pf	r	w	p
E	0.07	-1.62	-0.14	-0.13	-0.42	2.32
F	0.03	-0.11	-2.41	-0.01	0.33	2.20
K	0.20	-0.47	-0.05	-0.63	0.48	0.68
L	0.70	0.065	0.065	0.020	-0.171	0.02
q		-0.0405	-0.0484	-0.0032	-0.0022	0.0943

MINING

Table C7 Own- and cross price elasticites: Mining

	s	pe	pf	r	w	p
E	0.05	-1.42	-0.73	-0.16	-1.88	4.19
F	0.08	-0.97	-0.80	-0.07	-1.15	2.99
K	0.34	-1.14	-0.40	-0.91	-1.05	3.50
L	0.53	-1.20	-0.55	-0.10	-1.50	3.35
q		-0.3717	-0.1996	-0.0442	-0.4630	1.0782

Table C8 Own- and cross price elasticites – asymmetric energy price response: Mining

	s	pe	pf	r	w	p
E	0.05	-1.42	-0.73	-0.16	-1.93	4.24
F	0.08	-0.97	-0.80	-0.07	-1.15	2.99
K	0.34	-1.15	-0.40	-0.93	-1.06	3.54
L	0.53	-1.24	-0.55	-0.10	-1.53	3.42
q		-0.3758	-0.1996	-0.0447	-0.4727	1.0928