Purchase or Generate? An Analysis of Energy Consumption, Co-generation and Substitution Possibilities in Energy Intensive Manufacturing Plants under the Japanese Feed-in-Tariff

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Abstract

As the manufacturing industry is one of the largest contributors to global emissions, decarbonization of the production line is a key aspect in the fight against climate change. In this study, we examine the level of substitutability between fossil fuel and electricity. Using data on Japanese plants from 2004 to 2020, we estimate the elasticity of substitution between the two inputs, and find that a 1% increase in electricity prices results in a 6.55% increase in fossil fuel consumption. This is a unilateral form of substitution, as an increase in fossil fuel price does not translate in any significant changes in electricity consumption in the short-run. Our paper also contributes to explaining mechanisms behind inter-fuel substitution, with a special focus on electricity and fossil fuel through cogeneration. We find that substitutability is highly sector-dependent, and identify the pulp & paper, iron & steel, chemicals and cement to be sectors with substitution capacity. These sectors see an increase in their electricity generation, the magnitude of which is estimated between 0.004% (cement) to 0.23% (iron & steel). Iron & steel and cement also increase their consumption of coal to power generators by 0.06% and 0.005%, respectively.

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Purchase or generate? An analysis of inter-fuel substitution and electricity generation in Japanese manufacturing plants

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Highlights:

- A 1% increase in electricity prices results in a 6.55% increase in fossil fuel consumption inside manufacturing plants.
- An increase in fossil fuel price does not translate in any significant changes in electricity consumption in the short-term.
- Substitution is sector-dependent, and only plants from pulp & paper, iron & steel, chemicals and cement sectors are shown to have substitution capacity.
- These sectors see an increase in their electricity generation, the magnitude of which is estimated between 0.004% (cement) to 0.23% (iron & steel)

Abstract:

As the manufacturing industry is one of the largest contributors to global emissions, decarbonization of the production line is a key aspect in the fight against climate change. In this study, we examine the level of substitutability between fossil fuel and electricity. Using data on Japanese plants from 2004 to 2020, we estimate the elasticity of substitution between the two inputs, and find that a 1% increase in electricity prices results in a 6.55% increase in fossil fuel consumption. This is a unilateral form of substitution, as an increase in fossil fuel price does not translate in any significant changes in electricity consumption in the short-run. Our paper also contributes to explaining mechanisms behind inter-fuel substitution, with a special focus on electricity and fossil fuel through cogeneration. We find that substitutability is highly sector-dependent, and identify the pulp & paper, iron & steel, chemicals and cement to be sectors with substitution capacity. These sectors see an increase in their electricity generation, the magnitude of which is estimated between 0.004% (cement) to 0.23% (iron & steel). Iron & steel and cement also increase their consumption of coal to power generators by 0.06% and 0.005%, respectively.

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1. Introduction

Following the Fukushima Nuclear Accident, Japan entered an energy crisis, as many nuclear power plants were halted down. Electricity supply became temporarily unstable, and the country turned to fossil fuel imports in the short run. As a consequence, energy prices soared. While the energy crisis affected the Japanese economy as a whole, energy intensive (EI) manufacturing sectors were especially vulnerable. Following the earthquake, the government called for industrial sectors to voluntarily decrease their demand for electricity, so as to reduce the stress on the grid. Plants located in the Kanto and Tohoku regions also experienced rolling blackouts Government called for plants with generation capacity to assist the main power companies. Large companies tried to cope by organizing emergency supply of gas and gasoline to their northeastern plants, or simply by shifting the production to the western part of the country.

The aftermath of the shock did not bring much relief to the industry. While power supply stabilized, electricity price increased by 38%, between 2010 and 2014, due to oil price movements and the introduction of the renewable levy to finance the domestic Feed-in-Tariff. Calls for assistance of the manufacturing sector in electricity supply were still maintained, and manufacturers were encouraged to generate their own electricity. While the Greast East Japan Earthquake was a shock for the industrial sector, policies implemented in its aftermath very much encouraged manufacturers to produce their own power, through FIT subsidies for renewable biomass or subsidies for the installation of Combined Heat and Power (CHP) generators and energy efficiency. The combination of high electricity prices and incentives for on-site electricity generation may have encouraged manufacturing plants to substitute electricity from the grid with electricity generated inside the plant, powered by fossil fuel.

The hypothesis of substitution between energy inputs among plants of the manufacturing sector has been studied by Joskow (1984) and was followed by empirical study by Dismukes & Kleit (1999) and Hester & Gross (2001). However, following the rises in energy prices and the electrification of the manufacturing sector in recent years, the topic is resurfacing in the literature. This hypothesis is usually explored through the evaluation of cross-price elasticity among the fuels (Bardazzi et al., 2015; Kitamura and Managi, 2016; Li and Lin, 2016; Serletis et al., 2010) and is still debated among scholars. Some studies confirm the substitution possibility with positive and significant cross-price elasticity (Bardazzi et al. 2015), usually with macro-level data (Hattori, 2008; Kabe, 2019; Serletis et al, 2010). Recent studies using plant-level information tend to reject the hypothesis (Kitamura & Managi, 2016), deem it as marginal in the total energy consumption of the plant (Li & Lin, 2016) or sector-dependent (Moller, 2017).

In this study, we use plant-level data to estimate short-run elasticity estimates of cross-price elasticity between electricity and fossil fuel. Our contribution to the literature can be divided into four ways. First, by using plant-level electricity and fuel price in the elasticity analysis, we offer precise estimates of the short-run elasticity coefficients. Second, we provide a discussion on the mechanisms behind this substitution, in addition to elasticity estimates: we explore whether substitution occurs through increased on-site electricity generation, powered by fossil fuel. While many studies on the topic examine the manufacturing sector as a whole (Bardazzi et al., 2015; Li and Lin, 2016; Serletis et al., 2010), we consider individual manufacturing sectors such as iron and steel, chemicals or pulp and paper. Substitution mechanisms are highly sector-dependent, and vary depending on the electricity generation technology, thus it is necessary to analyze each sector separately. Finally, through a fuel analysis, we discuss how the consumption of each individual fuel is affected by a rise in electricity price, and how this change varies across manufacturing sector.

The study is organized as follows: section 2 provides a literature review of the substitution mechanisms inside EI manufacturing plants. Section 3 describes the data and the methodology used in this study. Section 4 shows the estimation results and Section 5 discusses potential implications from our study. Section 6 concludes this study.

2. A review of substitution mechanisms in EI manufacturing plants

Before showing elasticity estimates, this study first explores the channels through which substitution may occur. In the case of manufacturing plants, they can use fossil fuel as a material input or as an input in electricity generators and boilers. We describe each fossil fuel usage channel separately, and provide details on potential substitution possibility between electricity and fossil fuel.

2.1 Substitutability between fossil fuel and electricity as material input

Research on the topic of decarbonization of EI industry also thus flourished in recent years, and include several analyses of potential substitution technologies of fossil fuel as a material input. For instance, Garcia-Olivares (2015) provides a detailed review of the fossil fuel needs for each energy intensive industries.

In the case of iron and steel plants, Fan and Friedmann (2021) distinguish three different processes for steel production: blast furnace or basic oxygen furnace (BF-BOF) almost fully relies on coal; electric arc furnace (EAF) which can use electricity as an alternative to coal; and direct reduced iron (DRI), which does not necessitate the use of furnace but uses natural gas or coal in the reduction process (Fan and Friedmann, 2021). BF-BOF represents nearly 71% of global crude steel production and drives the demand of this sector for coke, used as reductant in the oxidation-reduction reaction (Fan and Friedmann, 2021). Similarly, non-ferrous metal production also uses coal for metal reduction (Garcia-Olivares, 2015). EAF is mostly used for producing recycled steel, and represent 24% of global steel production, but, due to its need for steel scraps as basic input, cannot fully replace BF-BOF as dominant process (Fan and Friedmann, 2021). We refer the reader to Garcia-Olivares (2015) for a more detailed discussion on the potential alternatives to coal in in non-ferrous metal production.

Regardless of the output, many chemical factories must rely on naptha or coal for conventional production (Garcia-Olivares, 2015). However, there is a possibility to electrify some portions of the production, for instance, through electrochemistry rather than petrochemistry (Schiffer and Manthiram, 2017). In this process, electricity can be used as a replacement for thermochemical methods, which necessitates high amount of heat, and drive chemical reactions at relatively low temperature (Schiffer and Manthiram, 2017). Authors show that such procedure can be used for ammonia, but similar process may also be applied for the production of methanol or ethylene (Schiffer and Manthiram, 2017). Still, Garcia-Olivares (2015) maintains that basic input for production (naptha) is still necessary, although it can be replaced with lower carbon alternatives such as charcoals, or by using biological substitutes for fossil fuel (Garcia-Olivares, 2015). If solutions exist for decreasing the role of fossil fuel in production, it would seem that they still remain in pioneering stages, and are not widely spread in the current production lines.

Regarding pulp and paper production, there seems to be a high level of substitutability between fuel (excluding wood) and electricity for producing steam necessary for the production process, which is mostly used in drying (Rahnama Mobarakeh et al., 2021). For instance, Garcia-Olivares (2015) suggest that no production process require fossil fuel per se, and the entirety of the production line could be electrified in the future. Still, Rahnama Mobarakeh et al. (2021) highlights that pulp and paper require energy for steam generation, for which fossil fuel is needed, as a more efficient input. However, in recent years, this particular industry has striven to replace fossil fuel with renewable energy or biofuel in order to reduce emissions (Rahnama Mobarakeh et al, 2021).

Finally, non-metallic minerals such as cement or glass use most of their energy in the transformation of raw material such as lime or sillica through crushing, calcination, clinkering and final milling (Garcia-Olivares (2015). Technically, since calcination and clinkering can be electrified process, the whole line of cement could be electrified, but the efficiency of such process is not entirely guaranteed (Garcia-Olivares (2015).

Overall, this section highlights that, in order to substitute fossil fuel (as material input) with electricity, a plant would require some heavy technological investment to replace their existing equipment, and that many processes that allow for such substitution are still in pioneering stages or may not guarantee the same production efficiency. Hence, in the few months that followed the Fukushima nuclear disaster, it is unlikely that plants were capable of substituting electricity with fossil fuel in the material process, as a response to tighter power supply and price spikes.

2.2 Substitution through onsite electricity generation

In this study, we focus on another potential source of substitution: we posit that plants facing relatively high electricity prices may have attempted to replace electricity purchased from the market with electricity generated on site. This section describes the production technology behind power generation inside EI manufacturing plants, and is partially based on interviews conducted with inside plants from the chemical and iron and steel sector between March 2022 and January 2023.

A first way of generating electricity inside EI plants is through cogeneration or combined heat and power (CHP). This is a common practice among many sectors that require both energy and heat or steam in production, as CHP can provide both at the same time. Figure 1 below shows the share of each major industrial sector in the total electricity produced through CHP. Apart from the energy sector, we can see that the chemical sector and machinery sectors are the main electricity producers through CHP, followed closely by iron, steel and non-ferrous metals, electronics or electrical equipment and pulp and paper. Since iron & steel, pulp & paper, chemical plants and cement are the largest electricity producers among manufacturing sector in Japan[3], we provide more details on the generation methods for these four sectors. CHP generation in the chemical sector and cement occurs through fossil fuel-powered boilers, using waste gas and heat from the production process. In Japanese plants, coal or LNG are mostly used to power these boilers. Then, electricity and steam are produced through steam turbines. Recent attempts to reduce GHG emissions have resulted in chemical plants using gas turbines and waste heat boilers (powered by waste water) for CHP as well. CHP is preferred by petrochemical plants as it requires the same material input (coal, LNG) as the production process, and generally, electricity produced from CHP is cheaper than that of the market. Similar process is used in the iron and steel sector, using recovered heat from coke ovens and BF-BOF to power electricity and steam turbines. Interviews with plant managers revealed that electricity generated on site is far cheaper than purchasing it from power companies, due to the use of byproducts already present in the plant. However, for chemical and iron & steel and cement sectors, the amount of electricity produced through CHP cannot entirely cover the plants' energy needs, so the remaining amount is purchased through power companies. Interviews with

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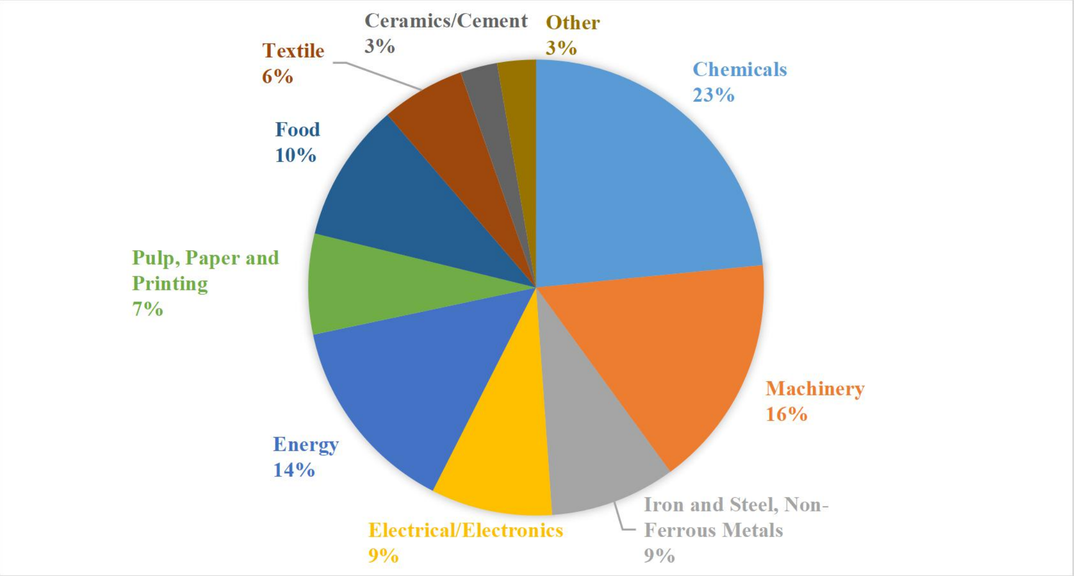
[3] https://www.meti.go.jp/shingikai/enecho/denryoku_gas/denryoku_gas/pdf/046_04_01.pdf

managers showed that roughly half of respondents whose plants is equipped with CHP believe that an increase in electricity or fuel price would have a great impact on their production (Ida & Kinoshita, 2007).

Figure 1. Share each sector in total electricity generated through CHP



Source' authors' compilation, based on data from ACEJ (2023).

The majority of electricity produced by the pulp and paper sector, on the other hand, does not come from CHP but from thermal generation and biomass. Integrated paper mills producing pulp from wood chips have a large amount of waste material that can be used in biomass waste or black liquor boilers. In addition, paper plants may also have CHP or fossil fuel-powered boilers. In the case of the paper industry, the main fuel input for boilers remains coal (26.2% of total energy consumption), followed by natural gas (6.3%) and heavy oil (5.5%)[4]. It is common for integrated paper mills to be nearly fully or fully independent when it comes to their energy needs. Some may even sell the excess electricity back to the grid. Overall, purchased power solely represents 8.4% in the total energy consumption of paper plants. Thus, paper plants were not as affected in the aftermath of March 11th as other sectors. In fact, since the FIT policy covers electricity produced from biomass, pulp and paper plants have gained a new incentive to sell their additional electricity to the grid. Through their interviews, Ida and Kinoshita (2007) showed that this production channel is not sensitive to changes in energy prices: 69.9% and 71.3% of respondents said their electricity generation using byproducts and waste would not be affected by a 10% increase in electricity or fuel prices, respectively.[5]

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[4] https://www.meti.go.jp/shingikai/enecho/denryoku_gas/denryoku_gas/sekitan_karyoku_wg/pdf/003_07_00.pdf

[5] It is possible that some plants adjust their electricity production powered via byproducts by affecting

In addition to CHP or thermal generators, some plants have also installed renewable energy installations. For instance, Tokyo Steel installed some solar panel in its Utsunomiya and Kitakyushu plants in 2020[6]. Chemical and petrochemical firms such as ENEOS or Mitsui Chemicals are also reported to have installed solar PV on rooftops of factories or remaining available space. Electricity can be sold back to the grid at a relatively high price, but some chemical companies are considering installing renewable energy to produce green hydrogen in an attempt to decarbonize their production line. Once installed, however, intermittent renewable energy production is not easy to forecast, thus, it is unlikely that substitution attempts could come from this channel.

Interviews inside the plants and a review of the generation systems installed inside Japanese plants showed that substitution could occur if energy prices were to rise. However, not every generation channel can provide this mitigation method, as only CHP and thermal generation offer enough leeway in the generation amount. Other method (byproduct gas, renewable energy, waste material) largely depend on manufacturing production or weather variations, which are not easily adjustable[7]. Any adjustment to replace purchased power must therefore be powered with fossil fuel, hence, we extent our analysis to fossil fuel used to power CHP generators, in addition to electricity generated on site.

3. Methodology

3.1 Elasticity estimation

Our main objective is to estimate the traditional own-price elasticity coefficients, defined as follows:

$$\begin{cases} \sigma^{elec\_elec} = (\partial y^{elec} / \partial p^{elec}) \\ \sigma^{fuel\_fuel} = (\partial y^{fuel} / \partial p^{fuel}) \end{cases} \tag{1}$$

where $y^{\bullet}$ represents the total consumption of the associated energy input and $p^{\bullet}$ represents the associated price. '*elec*' and '*fuel*' represents electricity and fossil fuel, respectively.

To examine the potential substitutability of electricity and fossil fuel, our focus is to evaluate the cross-price elasticity coefficients, defined as:

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the . For instance, pulp plants can lower the quality of the pulp and increasing the calorific value of black liquor, thereby having a more efficient electricity production.

[6] https://project.nikkeibp.co.jp/ms/atcl/19/news/00001/01170/?ST=msb

[7] The majority of renewable installations approved under the FIT program are intermittent renewable energy such as solar or wind in Japan. A minority of plants may also generate energy through small to medium-scale hydropower.

$$\begin{cases} \sigma^{elec\_fuel} = (\partial y^{elec} / \partial p^{fuel}) \\ \sigma^{fuel\_elec} = (\partial y^{fuel} / \partial p^{elec}) \end{cases} \tag{2}$$

Unlike Kitamura and Managi (2016), we do not assume the symmetry of elasticity estimates, that is σ^{elec_fuel} may not be equal to σ^{fuel_elec}. Such an assumption would imply that replacing electricity with fossil fuel (and vice versa) is achieved through the same channel. Section 2 showed that this is not necessarily the case, and it highly depends on the electricity generation type and technology used. Hence, we believe the symmetry assumption to be too strong, and we relax it to ensure the generality of our results.

In this study, we use a simple log-log model to estimate the short-term elasticities. We estimate the following system of equation by Ordinary Least Square (OLS):

$$\begin{cases} \ln(y_{it}^{elec}) = \alpha + \beta_1 \ln(p_{it}^{elec}) + \beta_2 \ln(p_{it}^{fuel}) + \theta X_{it} + \gamma_i + \eta_t + \varepsilon_{it} \\ \ln(y_{it}^{fuel}) = \alpha + \beta_1 \ln(p_{it}^{fuel}) + \beta_2 \ln(p_{it}^{elec}) + \theta X_{it} + \gamma_i + \eta_t + \varepsilon_{it} \end{cases} \tag{3}$$

where X_{it} is a vector containing some plant-level characteristics of plant *i* at time *t*, γ_i is a plant fixed effect, η_t is a time fixed effect and ε_{it} is an error term.

In equation (3), β_1 represents the own-price elasticity, that is, the elasticites presented in equation (1). Similarly, β_2 are the cross-price elasticities that we defined in equation (2). While own-price elasticities (β_1) are expected to be negative, the signs of estimated cross-price elasticities (β_2) should reveal whether electricity and fossil fuel complementary (negative sign) or substitute (positive sign) in the production process.

3.2 Data

This paper combines two different databases, all provided by the Ministry of Economy, Trade and Industry (METI). We use the *Current Survey of Energy Consumption* (CSEC), which provides information on monthly energy consumption of Japanese plants belonging to EI sectors (Agency for Natural Resources and Energy, 2023), as well as the

Census of Manufacture (CEM)[8], which is a yearly repository for economic variables at the plant level, across all manufacturing industry (METI, 2023a; 2023b). Our data covers all EI manufacturing plants across Japan, between April 2004 and March 2020, for a total of 220,720 observations. Appendix A provides more details regarding the building of the dataset.

The CSEC provides very detailed description of energy consumption inside plants: it contains the quantity of fuel, electricity and steam consumed for each month, and the plant also describes the usage target of each energy input, while the CEM offers plant-level information regarding industrial output, costs, labor and capital inputs. Using the CSEC, we can calculate how much fossil fuel was used to power CHP and other thermal generators. This particular indicator is crucial to evaluate whether the substitution hypothesis holds, as Section 2 showed that only CHP and thermal generators (powered by fossil fuel) offered enough flexibility for plants to adjust their electricity generation. The CSEC survey is also used by Kitamura & Managi (2016) and Mortha et al. (2022) in their studies of Japanese EI industries.

When calculating the elasticity of energy demand, the choice of energy price is crucial to ensure reliable estimates. To this end, we combine the information on electricity (fossil fuel) consumption from the CSEC and the data on electricity (fuel) costs as reported in the CEM. Using these two sources, we divide costs by consumption, and obtain a yearly average of the electricity and fossil fuel prices faced by the plant. This is a departure from previous plant-level studies on elasticity such as Kitamura & Managi (2016) who used aggregate electricity prices at the regional level.

Finally, we need to control for the plant characteristics that could affect its demand for electricity, as well as the amount of power generated on site. We select the total number of employees inside the plant (labor input), capital value (capital input), shipment value (industrial output) and the energy intensity of production (as a proxy for the technological level inside the plant). All control variables are retrieved from the CEM. Despite our best efforts, it is possible that our control variables may not capture all factors affecting the energy consumption of the plant. Thus, we also include a time fixed effect (fiscal year and month) as well as a plant fixed effect.

3.3 Estimation methodology

Table 1 below provides the summary statistics for our main dependent variables, energy price and other control variables. We use three types of dependent variables: energy consumption, variables related to electricity generation, and fuel used for electricity

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[8] Once every five years, the Census of Manufacture is replaced by the Census of Economic Activities, which covers all economic facilities in the country, including manufacturing ones.

generation on-site. We look at the amount of electricity generated on site, fossil fuel consumed to power cogenerators[9], byproducts, coal, oil and gas that are used for electricity generation. Our sample contains, at most, 220,720 observations across 1,607 plants. The largest sectors represented in the sample are machinery (539 plants), iron & steel (374 plants), pulp & paper (212 plants) and chemical products (211 plants). We refer the reader to Appendix A (Table A1) for the complete description of the sector distribution within our sample.

Table 1. Summary statistics

Panel 1A. Dependent variables

	Variable	Obs.	Mean	Std. Dev.	Min	Max	Number of zero -valued obs.
Elasticity estimation	Electricity consumption (1000 kWh)	220,720	13,996.75	39,350.12	0	87,7270	1,999
	Fossil fuel consumption (MJ)	220,720	486,310.1	2,409,789	0	3.86E+07	20,245
	Electricity generated (1000 kWh)	220,720	8,644.53	35,191.04	0	913,964	109,759
	Fossil fuel for electricity generation (MJ)	220,720	99,241.35	416,794.1	0	1.10E+07	99,578
Fuel analysis	Byproduct consumption for electricity generation (MJ)	220,720	36,052.39	173,008.6	0	4,079,603	199,072
	Coal consumption for electricity generation (MJ)	220,720	38,090.37	317,943.2	0	1.10E+07	205,946
	Oil consumption for electricity generation (MJ)	220,720	14,685.54	84,524.42	0	2,739,295	150,129
	Gas consumption for electricity generation (MJ)	220,720	10,413.05	41,235.46	0	1,042,695	157,334

Panel 1B. Control variables

Variable	Observations	Mean	Standard Deviation	Min.	Max.
Electricity price (JPY/kWh)	211,768	18.59	60.77	0	2708.42
Fuel price (JPY/MJ)	195,724	1.91	3.91	0	59.33
Employees inside plant	220,720	656.18	1364.82	0	29,667

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[9] This particular variable only considers “non-process” fuels in the CSEC survey, that is, fuels that are not byproducts generated during production.

Shipment value (10,000JPY)	220,720	7,148,723	2.62E+07	1,556	9.16E+08
Capital value (10,000JPY)	220,387	3,825,064	8,859,823	0	6.57E+07
Energy intensity of production (MJ/10,000JPY)	220,492	1.25	4.30	0	557.55

Source: authors' compilation. Figures are rounded to two decimals.

Since these plants belong to the manufacturing sector, many of them do not have the capacity to generate electricity. Roughly half of our sample shows zero-valued observations for electricity generation (and fossil fuel used for generation). This issue is especially acute when we consider cogeneration by fuel, as this is directly linked with the plant's available technology. For instance, roughly 93.31% of plants never use coal to generate electricity. In the case of non-linearity of the dependent variable, the use of the traditional OLS estimate is not advised, as it will suffer from a severe downward bias (Wooldridge, 2010). Transforming the dependent variable into their logarithmic form is also not recommended, as zero-valued observations will be dropped. In their application to trade data with many missing or zero-valued trade flows and non-negative values, Santos-Silva & Tenreyro (2006) showed that using Poisson Pseudo-Maximum Likelihood (PPML) estimator with robust (clustered) standard errors led to the most consistent estimator[10]. Therefore, this study uses PPML with conditional fixed effect to estimate equation (3) with generation and fuel dependent variables.

4. Results

4.1 Elasticity estimates

We first discuss elasticity estimates, that is, coefficients from the estimation of equation (3). Overall, we observe that most of the estimates are statistically significant, and negative, as per expected. A 1% increase in electricity (fuel) price would results in a 8.15%[11] (16.89%) decrease in electricity (fossil fuel) consumption in the manufacturing sector as a whole.

Table 2 - own-price elasticity

	Electricity consumption		Fossil fuel consumption	
	β_1	Sample size and	β_1	Sample size and

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[10] While Poisson is traditionally used for count data (non-negative integers) and data following a Poisson process, Santos-Silva & Tenreyro (2006), as well as Wooldridge (2010) show that the use of Poisson regression can be extended to non-Poisson data (as long as clustered errors are used) and non-integer data as well.

[11] Since the dependent variable is in logarithmic form, we obtaining the marginal effect of each coefficients by calculating (exp(β)-1)×100. All marginal effects in the main body are calculated as such.

		Adj. R-squared		Adj. R-squared
Manufacturing, all	-0.0850***	181,607 (1,388)	-0.185***	180,806 (1,388)
	(0.0145)	0.126	(0.0259)	0.163
Iron and steel	-0.0946**	41,606 (295)	-0.189***	41,548 (295)
	(0.0379)	0.149	(0.0466)	0.215
Machinery	-0.149***	57,099 (502)	-0.170***	56,614 (502)
	(0.0278)	0.231	(0.0396)	0.258
Chemical fibers	0.00632	6,959 (49)	-0.154**	6,935 (49)
	(0.0284)	0.219	(0.0672)	0.194
Paper and pulp	-0.0875**	30,127 (201)	-0.212***	30,089 (201)
	(0.0377)	0.159	(0.0707)	0.224
Glass	-0.197***	6,163 (43)	-0.309**	6,162 (43)
	(0.0662)	0.384	(0.143)	0.241
Chemicals	-0.0308	20,200 (157)	-0.213***	20,065 (157)
	(0.0204)	0.136	(0.0725)	0.191
Cement	-0.0741***	12,782 (91)	-0.138**	12,765 (91)
	(0.0267)	0.314	(0.0691)	0.263
Petrochemicals	-0.0207	4,919 (37)	-0.206	4,897 (37)
	(0.0267)	0.288	(0.144)	0.279
Non-ferrous metals	-0.0516	7,558 (61)	-0.106**	7,538 (61)
	(0.053)	0.125	(0.049)	0.205

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis); adjusted R-squared is shown on the second line.

We also obtain sector-specific estimates, and we show different levels of vulnerability to energy price shocks across sectors and across energy source, with estimated decrease ranging from -7.14% (cement, electricity) to -26.58% (glass, fossil fuel). In general, it appears that manufacturing sectors are more vulnerable to fossil fuel price shocks: estimated consumption decrease estimated between from -10.06% (non-ferrous metal) to -26.58% (glass). The glass sector is shown to have the highest elasticity, with estimated consumption decrease in electricity and fossil fuel being -17.88% and -26.58%, respectively. Chemical products, non-ferrous metal and chemical fibers are shown to be only vulnerable to fossil fuel price shocks (-19.18%,-10.06% and -14.27%, respectively), a fact that could be explained by their high reliance on fossil fuel as material inputs in the production process. Interestingly, iron & steel and pulp & paper sectors are shown to be highly vulnerable to fossil fuel price shocks (-17.22% and -19.10%, respectively), but far less affected by electricity price increase (-9.03% and -8.38%, respectively). This result might be explained by the reliance on fossil fuel as material inputs in the production for iron & steel, or the relatively high electricity generation capacity of some pulp plants. Overall, our results are of similar magnitude as previous literature on the topic, albeit a little smaller than Hoshino (2013)'s long-term elasticity estimates.

Table 3 - cross-price elasticity

	Electricity consumption		Fossil fuel consumption	
	β_2	Sample size and Adj. R-squared	β_2	Sample size and Adj. R-squared
Manufacturing, all	-0.00798	181,607 (1,388)	0.0634***	180,806 (1,388)
	(0.00714)	0.126	(0.0194)	0.163
Iron and steel	-0.00419	41,606 (295)	0.0832*	41,548 (295)
	(0.0116)	0.149	(0.0452)	0.215
Machinery	0.000791	57,099 (502)	0.0516	56,614 (502)
	(0.00963)	0.231	(0.0394)	0.258
Chemical fibers	-0.0664**	6,959 (49)	0.0617	6,935 (49)
	(0.0291)	0.219	(0.0374)	0.194
Paper and pulp	-0.00606	30,127 (201)	0.114***	30,089 (201)
	(0.0162)	0.159	(0.0312)	0.224
Glass	0.00934	6,163 (43)	0.108	6,162 (43)
	(0.0474)	0.384	(0.118)	0.241
Chemicals	-0.0308	20,200 (157)	-0.0335	20,065 (157)
	(0.0204)	0.136	(0.0519)	0.191
Cement	-0.0156	12,782 (91)	-0.084	12,765 (91)
	(0.0183)	0.314	(0.0518)	0.263
Petrochemicals	-0.0438	4,919 (37)	0.0278	4,897 (37)
	(0.0674)	0.288	(0.0559)	0.279
Non-ferrous metals	-0.00942	7,558 (61)	-0.0293	7,538 (61)
	(0.0195)	0.125	(0.0324)	0.205

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis); adjusted R-squared is shown on the second line.

We turn our attention to the estimates of cross-price elasticity. First, we note that there is a stark contrast in estimates for electricity and fossil fuel, which seemingly confirm that the symmetry assumption may be too strong. In general, a surge in fossil fuel price does not seem to affect electricity consumption. The only statistically significant coefficient for is σ^{elec_fuel} for chemical fibers: a 1% increase in fossil fuel prices reduces electricity consumption by 6.42% For this particular, it appears that electricity and fossil are complementary inputs. On the other hand, we observe three instances in which σ^{fuel_elec} is statistically significant and positive. A 1% rise in electricity prices results in a 6.55% increase in fossil fuel consumption for the manufacturing sector as whole. This result is arguably smaller than Serletis et al. (2010) or Bardazzi et al. (2015) but more in line with Li & Lin (2016), whose estimates range between 2.72% to 6.68% (depending on the fuel). However, this figure rises to 12.08% and 8.68% when considering the pulp & paper and iron & steel sectors, respectively. The positive sign and statistical significance indicate that replacing electricity with fossil fuel may be possible for these two sectors.

4.2 Electricity generation and energy prices

A review of the literature in Section 2 established that short-term substitution could only be possible through electricity generation on-site, powered by fossil fuel. In this section, we examine how a change in energy price affects the amount of electricity generated on-site as well as the consumption of fossil fuel used to power electricity generators. Equation (3) is re-estimated through PPML with the new dependent variables and shown in Table (4) and (5).

Table 4. own-price elasticity (generation)

Coefficients associated with fuel price	Electricity generation		Fossil fuel for electricity generation	
	β_1	Sample size	β_1	Sample size and Adj. R-squared
Manufacturing, all	0.000705 (0.0136)	118,737 (879)	-0.207*** (0.0480)	129,654 (943)
Iron and steel	-0.272** (0.121)	8,931 (56)	-0.321*** (0.0971)	19,515 (136)
Chemical fibers	-0.428** (0.171)	5,202 (32)	-0.367** (0.149)	6,759 (46)
Paper and pulp	-0.0818 (0.0551)	19,197 (121)	-0.259*** (0.0586)	30,663 (203)
Glass	-0.0498 (0.0822)	2,124 (13)	-0.725*** (0.276)	3,249 (23)
Chemicals	-0.272** (0.133)	15,000 (98)	-0.208** (0.0877)	17,751 (124)
Cement	-0.281* (0.156)	7,189 (44)	-0.336*** (0.124)	8,878 (58)
Non-ferrous metals	0.00241 (0.0405)	2,642 (15)	-0.214*** (0.0692)	2,789 (18)

Source: authors' compilation. Estimation method: Poisson Regression with conditional plant fixed effects. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis). Plants with zero outcome throughout the study period are automatically dropped from the estimation, thus, the sample should be understood as ‘manufacturing plants with generation capacity’.

We first present estimates of own-price elasticities, which are all negative and range from -18.70% (chemicals, fossil fuel) to -51.57% (glass, fossil fuel). This finding confirms that electricity generation is sensitive to changes in fuel prices. Chemical fibers has the largest estimates, with -34.82% and -30.72% for electricity and fossil fuel, respectively. Once again, we obtain statistically significant estimates for fossil fuel in the pulp & paper sector (-22.82%), but not for electricity generation. This could be coming from the fact that many pulp plants generate electricity via byproducts and waste. It would indicate that the pulp & paper can potentially cushion electricity price shocks through generation.

Table 5. cross-price elasticity (generation)

Coefficients associated with electricity price	Electricity generation		Fossil fuel for electricity generation	
	β_2	Sample size and Adj. R-squared	β_2	Sample size and Adj. R-squared
Manufacturing, all	0.000102**	118,737	0.000102**	129,654
	(0.0000403)	(879)	(0.0000420)	(943)
Iron and steel	0.00230***	8,931	0.00241***	19,515
	(0.000500)	(56)	(0.000623)	(136)
Chemical fibers	0.000190	5,202	0.0000422	6,759
	(0.000227)	(32)	(0.000144)	(46)
Paper and pulp	0.000238**	19,197	0.000192**	30,663
	(0.000120)	(121)	(0.0000896)	(203)
Glass	0.00315	2,124	-0.00409	3,249
	(0.0254)	(13)	(0.0234)	(23)
Chemicals	0.000145*	15,000	0.0000468	17,751
	(0.0000796)	(98)	(0.0000512)	(124)
Cement	0.0000385***	7,189	0.0000332***	8,878
	(0.0000101)	(44)	(0.00000899)	(58)
Non-ferrous metals	0.00287	2,642	0.0378**	2,789
	(0.00177)	(15)	(0.0181)	(18)

Source: authors’ compilation. Estimation method: Poisson Regression with conditional plant fixed effects. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. “*”, “**” and “***” represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis). Plants with zero outcome throughout the study period are automatically dropped from the estimation, thus, the sample should be understood as ‘manufacturing plants with generation capacity’.

Cross-price elasticities related to generation help draw a more complete picture of mechanisms behind the substitution of electricity and fossil fuel. A 1% increase in electricity price is followed by a 0.01% increase in both electricity generation and fossil fuel to power generators. This figure becomes 0.02% for the pulp & paper sector and 0.23-0.24% for the iron& steel sector. We also note statistically significant coefficients for the non-ferrous metal sectors for fossil fuel consumption (3.85%) but it does not translate into electricity generation. On the contrary, the chemical sector increases their electricity generation by 0.01%, though we fail to see an increase in fossil fuel consumption.

4.3 Fuel analysis

In this section, we analyze the change in fossil fuel per source. We consider four dependent variables: byproducts, coal, oil and gas, all used to power electricity generators. PPML estimates of cross-price elasticity from equation (3) with these new dependent variables are presented in Table (6). We provide more details on the fuel analysis, including the fuel classification and the own-price elasticity estimates in Appendix C.

Table 6. cross-price elasticity (fuel analysis)

Coefficients associated with electricity price	Byproducts		Coal		Oil		Gas	
	β_2	Sample size	β_2	Sample size	β_2	Sample size	β_2	Sample size
All sectors	0.000264 (0.000182)	21,269 (156)	0.0000342 (0.0000248)	14,502 (102)	-0.000380* (0.000228)	68,492 (691)	0.000131 (0.000111)	62,304 (541)
Iron and steel	0.00242** (0.00111)	2,832 (19)	0.000637** (0.0003)	1,604 (11)	-0.00154 (0.0035)	7,618 (76)	0.00475 (0.00561)	11,027 (93)
Chemical fibers	0.00102 (0.00383)	449 (4)	0.0000457 (0.000183)	2,367 (14)	-0.000957** (0.000461)	4,860 (43)	0.000838*** (0.00012)	2,628 (24)
Paper and pulp	0.000437*** (0.000104)	8,707 (62)	0.0000148 (0.0000898)	5,707 (41)	-0.00258** (0.00111)	19,670 (175)	0.000231 (0.000151)	12,438 (97)
Chemicals	-0.000107 (0.000299)	7,975 (61)	-0.000028 (0.0000352)	3,241 (23)	-0.000163 (0.000257)	10,211 (97)	-0.0000692 (0.000051)	7,857 (63)
Cement	0.00181 (0.00163)	226 (3)	0.0000469*** (0.0000101)	2,201 (15)	-0.00124 (0.00178)	5,687 (55)	0.0211*** (0.00498)	641 (7)

Source: authors' compilation. Estimation method: Poisson Regression with conditional plant fixed effects. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis).

A first observation that can be drawn from these results is the high level of heterogeneity across manufacturing sectors. Unlike in previous sections, we fail to observe a general trend with estimates of the overall manufacturing sector, with the notable exception of oil (-0.04%, marginally significant). This heterogeneity is likely to be due to the difference in electricity generation technology that was described in Section 2: some sectors (pulp & paper, iron & steel) are heavily relying on byproducts for electricity generation while others do not generate enough useful waste in their production process. Overall, we observe that chemical fibers and pulp & paper are reducing the use of oil by -0.10% and -0.26% in the event of a rise in electricity prices. While chemical fibers are shown to increase their gas consumption (+0.08%), pulp & paper increase their consumption of byproducts (+0.04%). A similar observation is drawn for the iron & steel sector, with an increase in byproducts (+0.24%) and coal consumption (+0.06%). Cement manufacturers are also shown to increase their consumption of coal (+0.005%) while reducing their consumption of gas (-2.09%).

5. Discussion

In this study, we find that a 1% increase in electricity prices results in a 6.55% increase in fossil fuel consumption in the manufacturing sector. This finding implies that electricity and fossil fuel can be thought as substitutable inputs in the production process, to an extent. In addition, we found that an increase in fossil fuel price did not trigger changes in electricity consumption, which suggests the existence of unilateral substitutability between the two energy inputs. This particular finding could be explained in two ways: electrification cannot be achieved in the short-term, and thus is not captured by our short-run elasticity estimates. Alternatively, it could also be due to the heavy carbon content of the Japanese electricity mix, especially after 2011. A surge in fossil fuel prices may also affect the electricity prices, making it difficult to entangle the substitution effect and the electricity price effect in the estimation.

Mechanisms behind short-term substitution were elucidated in this study, as we showed that the increased fossil fuel consumption is due to a rise in fossil fuel to power electricity generators on site. A 1% increase in electricity price leads to a 0.01% rise in electricity generation, as well as a 0.01% rise in fossil fuel consumed to power generators. Though this result applies to the manufacturing sector as a whole, the estimates are very heterogeneous across individual sectors. We find that this substitution mainly occurs in the following sectors: iron & steel, pulp & paper, chemicals and cement. For each of these, electricity generation increases by 0.23%, 0.02%, 0.01% and 0.004%, respectively. The large difference in these estimates compared with the overall manufacturing ones shows that, when analyzing interfuel substitution, it is preferable to analyze individual industrial sectors separately to obtain more precise results. Furthermore, since we showed that increased electricity generation is the main substitution channel, studies on the manufacturing sector may have different conclusions depending on whether the study sample is restricted to plants with generation capacity.

Finally, we analyzed the change in the type of fossil fuel used in electricity generation, when electricity prices are on the rise. As the type of fossil fuel used in the generation process differs, the results vary widely across industrial sectors. Sectors that rely on byproducts like pulp & paper or iron & steel, tend to increase their consumption of waste when electricity prices rise. Coal consumption is shown to increase for iron & steel, as well as cement, while gas consumption is reduced for latter. Coal is more polluting than gas, hence, a rise in electricity prices might undermine decarbonization efforts. In fact, during the study period, Japan introduced a Feed-in-Tariff, financed through a renewable levy. Based on our elasticity estimation, it is possible that the introduction of this electricity tax may have had the unintended consequence of increasing fossil fuel usage in the EI sector. The exploration of the effect of the FIT levy on EI sectors is left for future studies to tackle.

Between the increase in fossil fuel consumption triggered by higher electricity prices and the rise in coal consumption, our finding could highlight the need for a more comprehensive taxation of fossil fuel, possibly in the form of carbon pricing. To be precise, Japan has introduced a carbon tax since 2012, but its rate is relatively low (289 JPY/tCO_2), and under this tax, coal is relatively cheaper than gas. Japan also introduced cap-and-trade programs in the Tokyo and Saitama prefectures, and is planning to introduce similar schemes at the national level starting with a pilot phase composed of voluntary firms (GX-ETS). In general, however, these schemes often target the power industry, and thus do not include the EI sectors with self-generation capacity that we studied. Hence, for the Japanese government to have an efficient and effective mitigation policy, we need a comprehensive carbon pricing policy, which include self-generation in EI sectors.

6. Concluding remarks

Decarbonization of industrial production is a key aspect in the fight against climate change. Electrification as well as the replacement of heavily polluting fuels like coal with relatively cleaner alternatives has been a point of focus in the manufacturing industry in recent years. This study examines whether fossil fuel and electricity are substitute inputs in industrial production. Using plant-level data from 2004 to 2020, we estimate the elasticity of substitution between these two inputs, and explore the mechanisms behind said substitution. We find that a 1% increase in electricity prices results in a 6.55% increase in fossil fuel consumption inside manufacturing plants. This increase is due to a rise in fossil fuel used to power electricity generators so that plants can produce their own electricity rather than purchasing it from the market. Interestingly, we find that this is a unilateral form of substitution, as an increase in fossil fuel price does not translate in any significant changes in electricity consumption. In other words, higher electricity prices are not correlated with higher electricity consumption in the manufacturing sector. This could imply that higher fossil fuel prices alone may not be enough to foster electrification of the manufacturing industry.

Substitutability is highly dependent on the industrial sector, and we identified iron & steel, pulp & paper, chemicals and cement as sector with substitution capacity. The type of fossil fuel used in this substitution also varies across sectors, as iron & steel and cement plants increase their consumption of coal (+0.06% and 0.005%, respectively), while pulp & paper increase their consumption of byproducts (+0.04%). As the Japanese electricity mix is increasingly relying on renewable energy, fossil fuel-powered electricity generation may undermine decarbonization efforts, especially if powered by coal or oil. In this sense, our findings may suggest the need for a more comprehensive taxation on fossil fuel alternatives, to ensure the use of clean electricity in industrial sectors. Carbon pricing on all manufacturing sectors would be one attractive policy choice.

These results, however, must be interpreted cautiously as half of our study period comprises the aftermath of the Fukushima nuclear disaster, an event that resulted in structural changes in the Japanese energy market. The changes include a conjunction of very high electricity prices, a higher level of intermittent, renewable sources in the electricity grid, as well as relatively low fossil fuel prices. Although we are controlling for energy prices as well as economic factors inside firms, it is possible that the conjunction of all these factors may have driven plants to substitute electricity with fossil fuel, to an extent. Thus, the elasticity estimates offered in this study could be considered as upper bound.

Our study has several limitations. Because the CEM survey is only conducted at a yearly frequency, the energy price used in this study should be understood as yearly average prices for a given plant. Though we control for seasonal variations in energy demand with a month fixed effect, this method may not perfectly capture monthly variations in energy consumption. We have also selected plants with generation capacity (in Poisson regression framework), so we do not model how the policy could have influenced plants' decision to install power generation equipment. Therefore, our study does not focus on upfront installation costs and potential subsidies[12] but only examines the impact of fuel costs on energy consumption and substitution. Finally, we cannot model the changes in efficiency of CHP generators due to technological improvements or increase in fuel efficiency[13], due to data limitations.

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[12] There are many subsidy schemes to encourage CHP installation in Japan, offered by the Ministry of Economy, Trade and Industry (METI), the Ministry of Environment, the Ministry of Land, Infrastructure, Transport and Tourism and by the Ministry of Internal Affairs and Communications.

[13] For instance, pulp plants can increase the calorific value of the produced black liquor by reducing

7. Acknowledgements

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8. Authors' contribution

Aline Mortha: conceptualization, methodology, software, data curation, investigation, writing - original draft, visualization, funding acquisition, editing; **Toshi H. Arimura**: supervision, funding and data acquisition, writing-review, and editing.

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the quality of produced fibers, and could generate more electricity with the same amount of fuel. In this study, we are using generic calorific values provided by METI and hence, cannot model these changes.

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10. Appendix

Appendix A. Dataset creation methodology

First, we transformed the CSEC database into a panel. For this survey, each plant receives an individual survey identifier, and must report their monthly consumption in a written or online survey questionnaire. The questionnaire format varies slightly across sectors. Some plants' classification is not very straightforward, as the sectors are somewhat porous (chemical and chemical fibers, iron & steel and machinery, etc.). Table A1 shows the sectoral distribution in our sample.

Table A1. Sectoral distribution inside sample

Sector	Number of observations	Number of plants	Share inside total manufacturing sample
Iron & steel	55,500	374	0.25
Machinery	63,304	539	0.29
Chemical fibers	8,484	56	0.04
Pulp & paper	32,063	212	0.15
Glass	6,693	46	0.03
Chemicals	30,046	211	0.14
Cement	15,949	106	0.07
Petrochemicals	5,889	41	0.03
Non-ferrous metal	9,494	73	0.04

Source: authors' compilation. Figures are rounded to two decimals for share values.

In this case, each plant fills in two different questionnaires. While in the majority of cases, the values reported in both questionnaires are the same, they sometimes differ: if the values differ, we choose to keep the maximum value. To reflect that some plants may belong to various sectors, we create sector dummies that are not mutually exclusive for a given plant identifier, i.e., a plant may belong to two or more sectors at once. Once we remove the duplicate observations due to multiple questionnaire filling, we obtain a panelized dataset. Then, we proceed with the creation of aggregate fossil fuel variables. The aggregation was realized by converting each fuel into its calorific value. Conversion coefficients are presented in Table A2.

Table A2. Conversion coefficients for calorific value

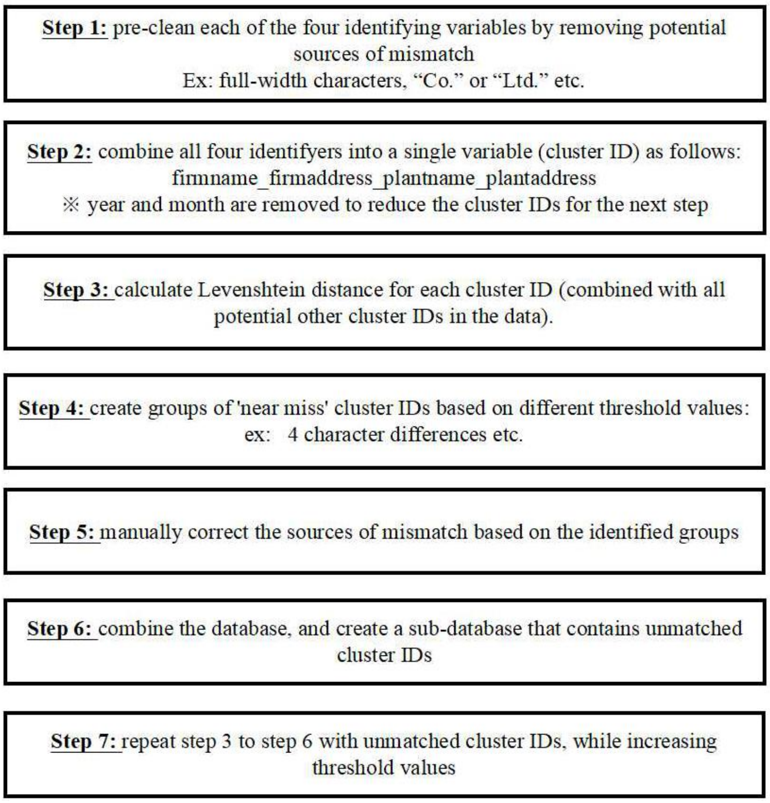
Fuel name	Coefficient	Fuel name	Coefficient	Fuel name	Coefficient
Crude oil	38.2 GJ/kl	LPG	50.8 GJ/t	Hydrocarbon gas (byproduct gas)	44.9 GJ/1000nm^3
NGL and condensate	35.3 GJ/kl	Oil coke	29.9 GJ/t	Gas from coke oven	21.1 GJ/1000nm^3
Gasoline	34.6 GJ/kl	Asphalt	40.9 GJ/t	Gas from blast furnace	3.41 GJ/1000nm^3
Naphtha	33.6 GJ/kl	Coal for coke production	29.0 GJ/t	Gas from converter	8.41 GJ/1000nm^3
Reformed product	35.1 GJ/kl	Coal	25.7 GJ/t	Gas from electric	8.41

oil				furnace	GJ/1000nm^3
Kerosene	36.7 GJ/kl	Coal coke	29.4 GJ/t	Natural gas	43.5 GJ/1000nm^3
Diesel	37.7 GJ/kl	Tar	37.3 GJ/t	Piped gas	44.8 GJ/1000nm^3
Heavy oil (A)	39.1 GJ/kl	LNG	54.6 GJ/t	Oxygen	7.12 GJ/1000nm^3
Heavy oil (B/C)	41.9 GJ/kl	Waste tire	33.2 GJ/t	Recovered black liquor	13.2 GJ/dry t
Hydrocarbon oil	41.9 GJ/kl	Waste plastics	29.3 GJ/t	Waste	16.3 GJ/dry t
Renewable oil	40.2 GJ/kl	RPF	29.3 GJ/t		

Source: authors' compilation based on documentation provided by the Agency for Natural Resources and Energy (2019) together with the database.

Then, we combine the CSEC with the CEM data. In Japan, these surveys are handled by two different agencies (Agency for Natural Resources and Energy and Ministry of Trade, Economy and Industry, respectively). Therefore, the individual identifier for each survey is different for a given plant, which makes the identification of the plant difficult. Because the data contains information on the name and physical address of the plant and its owning firm, we combine the database based on these information as well as the year and month. Figure A3 offers an overview of the matching procedure.

Figure A3. Fuzzy string matching procedure



Step 1: pre-clean each of the four identifying variables by removing potential sources of mismatch
Ex: full-width characters, “Co.” or “Ltd.” etc.

Step 2: combine all four identifyers into a single variable (cluster ID) as follows:
firmname_firmaddress_plantname_plantaddress
※ year and month are removed to reduce the cluster IDs for the next step

Step 3: calculate Levenshtein distance for each cluster ID (combined with all potential other cluster IDs in the data).

Step 4: create groups of 'near miss' cluster IDs based on different threshold values:
ex: 4 character differences etc.

Step 5: manually correct the sources of mismatch based on the identified groups

Step 6: combine the database, and create a sub-database that contains unmatched cluster IDs

Step 7: repeat step 3 to step 6 with unmatched cluster IDs, while increasing threshold values

Source: authors’ compilation.

With this matching procedure, we matched 80.68% of the CSEC sample with the CEM and 87.97% of the CSEC sample for the years when the Census of Economic Activities was implemented (FY2011 and FY2015). Some of the non-matched entities are public entities (prefectural buildings, water management facilities) that were not targeted by the CEM. Since the CSEC covers calendar years while the CEM is conducted for fiscal years, some of the unmatched observations are also from plants closing down during that particular fiscal/calendar year. We can identify such instances as reported values for the CSEC are nearly all “0” for most of the calendar year.

Appendix B. Elasticity estimates - before and after the introduction of Feed-in-Tariff

Table B1. Before the introduction of Feed-in-Tariff: own-price elasticity

	Electricity consumption		Fossil fuel consumption	
	β_1	Sample size and Adj. R-squared	β_1	Sample size and Adj. R-squared
Manufacturing, all	-0.0868***	97,261 (1,351)	-0.198***	96,762 (1,350)
	(0.0194)	0.141	(0.0334)	0.154
Iron and steel	-0.210**	21,917 (285)	-0.265***	21,889 (285)
	(0.0817)	0.204	(0.0697)	0.258

Machinery	-0.139***	31,692 (488)	-0.165***	31,378 (488)
	(0.0366)	0.265	(0.0412)	0.274
Chemical fibers	0.0143	3,548 (46)	-0.123	3,540 (46)
	(0.024)	0.160	(0.0914)	0.156
Paper and pulp	-0.0664	16,167 (200)	-0.294***	16,160 (199)
	(0.0444)	0.182	(0.103)	0.244
Glass	-0.225***	3,359 (43)	-0.178***	3,358 (43)
	(0.0748)	0.260	(0.0609)	0.241
Chemicals	-0.026	10,668 (151)	-0.157**	10,568 (151)
	(0.0222)	0.102	(0.0651)	0.114
Cement	-0.0731*	6,527 (88)	-0.111	6,510 (88)
	(0.0371)	0.263	(0.0743)	0.219
Petrochemicals	-0.0116	2,570 (37)	0.0432	2,566 (37)
	(0.0217)	0.392	(0.0383)	0.489
Non-ferrous metals	-0.0962**	4,063 (59)	-0.0691	4,044 (59)
	(0.0441)	0.203	(0.0618)	0.225

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis); adjusted R-squared is shown on the second line.

Table B2. Before the introduction of Feed-in-Tariff: cross-price elasticity

	Electricity consumption		Fossil fuel consumption	
	β_2	Sample size and Adj. R-squared	β_2	Sample size and Adj. R-squared
Manufacturing, all	-0.00834	97,261 (1,351)	0.0583**	96,762 (1,350)
	(0.00774)	0.141	(0.0236)	0.154
Iron and steel	-0.00708	21,917 (285)	0.073	21,889 (285)
	(0.0109)	0.204	(0.0907)	0.258
Machinery	0.00207	31,692 (488)	0.0477	31,378 (488)
	(0.0121)	0.265	(0.0451)	0.274
Chemical fibers	-0.0380**	3,548 (46)	0.052	3,540 (46)
	(0.0174)	0.160	(0.0515)	0.156
Paper and pulp	-0.0172	16,167 (200)	0.113***	16,160 (199)
	(0.0219)	0.182	(0.0417)	0.244
Glass	-0.0395	3,359 (43)	-0.0529	3,358 (43)
	(0.0485)	0.260	(0.056)	0.241
Chemicals	-0.0127	10,668 (151)	0.00792	10,568 (151)
	(0.0212)	0.102	(0.0379)	0.114
Cement	-0.0317	6,527 (88)	-0.0681	6,510 (88)
	(0.0251)	0.263	(0.047)	0.219
Petrochemicals	0.0646**	2,570 (37)	0.0289	2,566 (37)

	(0.0278)	0.392	(0.0187)	0.489
Non-ferrous	0.0178	4,063 (59)	-0.0365	4,044 (59)
metals	(0.0227)	0.203	(0.0302)	0.225

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis); adjusted R-squared is shown on the second line.

Table B3. After the introduction of Feed-in-Tariff: own-price elasticity

	Electricity consumption		Fossil fuel consumption	
	β_1	Sample size and Adj. R-squared	β_1	Sample size and Adj. R-squared
Manufacturing, all	-0.0280**	84,346 (1,127)	-0.116***	84,044 (1,127)
	(0.0124)	0.124	(0.0251)	0.134
Iron and steel	-0.0473*	19,689 (261)	-0.0894**	19,659 (261)
	(0.0269)	0.092	(0.0365)	0.156
Machinery	-0.0356*	25,407 (365)	-0.113***	25,236 (365)
	(0.0195)	0.189	(0.0323)	0.207
Chemical fibers	0.00738	3,411 (42)	-0.228**	3,395 (42)
	(0.0133)	0.255	(0.11)	0.223
Paper and pulp	-0.0644**	13,960 (170)	-0.0505	13,929 (170)
	(0.026)	0.327	(0.0393)	0.356
Glass	-0.000726	2,804 (35)	-0.594	2,804 (35)
	(0.0376)	0.515	(0.402)	0.204
Chemicals	-0.0205	9,532 (138)	-0.185**	9,497 (138)
	(0.0215)	0.154	(0.0834)	0.207
Cement	-0.0177	6,255 (78)	-0.101	6,255 (78)
	(0.0311)	0.421	(0.0628)	0.336
Petrochemicals	-0.0323	2,349 (35)	-0.242	2,331 (35)
	(0.0481)	0.295	(0.206)	0.259
Non-ferrous	-0.0359	3,495 (45)	-0.0432	3,494 (45)
metals	(0.0283)	0.226	(0.0323)	0.265

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis); adjusted R-squared is shown on the second line.

Table B4. After the introduction of Feed-in-Tariff: cross-price elasticity

	Electricity consumption		Fossil fuel consumption	
	β_2	Sample size and Adj. R-squared	β_2	Sample size and Adj. R-squared

Manufacturing, all	-0.00357	84,346 (1,127)	0.0508**	84,044 (1,127)
	(0.00774)	0.124	(0.0221)	0.134
Iron and steel	0.0135	19,689 (261)	0.0490*	19,659 (261)
	(0.0114)	0.092	(0.0293)	0.156
Machinery	-0.00577	25,407 (365)	0.0493*	25,236 (365)
	(0.00983)	0.189	(0.0261)	0.207
Chemical fibers	-0.117	3,411 (42)	0.0991***	3,395 (42)
	(0.0714)	0.255	(0.026)	0.223
Paper and pulp	0.000962	13,960 (170)	0.0480**	13,929 (170)
	(0.00912)	0.327	(0.0241)	0.356
Glass	-0.115	2,804 (35)	0.316	2,804 (35)
	(0.0729)	0.515	(0.21)	0.204
Chemicals	-0.0188	9,532 (138)	-0.0915	9,497 (138)
	(0.0258)	0.154	(0.0739)	0.207
Cement	-0.00194	6,255 (78)	0.022	6,255 (78)
	(0.0139)	0.421	(0.0829)	0.336
Petrochemicals	-0.0637	2,349 (35)	0.0369	2,331 (35)
	(0.0944)	0.295	(0.121)	0.259
Non-ferrous metals	-0.0239	3,495 (45)	-0.0428*	3,494 (45)
	(0.0369)	0.226	(0.024)	0.265

Source: authors' compilation. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis); adjusted R-squared is shown on the second line.

Appendix C. Supplementary material for fuel analysis

The CSEC provides data on fuel consumption by fuel, and fuel categories are too detailed for this analysis (diesel, naphtha, etc.). We thus aggregated these fuel into broader categories to provide a clearer picture of the change in fuel consumption patterns. Table C1 provides an overview of our classification method during the aggregation.

Table C1. Classification of fossil fuel used in the analysis

Classification	Byproduct material	Coal	Oil	Gas
Included fuel	Hydrocarbon oil Hydrocarbon gas Gas from coke oven Gas from blast furnace Gas from converter Gas from electric furnace	Oil coke Coal for coke production Coal Coal coke Tar	Crude oil Gasoline Naphtha Reformed product oil Kerosene Diesel	NGL and condensate LPG Natural gas LNG Piped gas

Recovered black liquor	Heavy oil (A)
Oxygen	Heavy oil (B/C)
Waste	Asphalt
Waste tire	Renewable oil
Waste plastics	
RPF	

Source: authors' compilation. Hydrocarbon oil and hydrocarbon gas are referred in the survey as 'byproducts' in the questionnaire, hence we place them among byproduct materials.

Table C2. own-price elasticity (fuel analysis)

	Byproducts		Coal		Oil		Gas	
	β_1	Sample size	β_1	Sample size	β_1	Sample size	β_1	Sample size
All sectors	-0.159**	21,269	-0.138***	14,502	-0.0704	68,492	-0.0592	62,304
	(0.0699)	(156)	(0.0484)	(102)	(0.052)	(691)	(0.0401)	(541)
Iron and steel	-0.137**	2,832	-0.034	1,604	0.173**	7,618	-0.31	11,027
	(0.059)	(19)	(0.0301)	(11)	(0.0809)	(76)	(0.191)	(93)
Chemical fibers	-0.0563	449	-0.434***	2,367	-0.121	4,860	-0.0071	2,628
	(0.0634)	(4)	(0.165)	(14)	(0.147)	(43)	(0.0362)	(24)
Paper and pulp	-0.530***	8,707	-0.0968*	5,707	-0.0178	19,670	-0.0417**	12,438
	(0.203)	(62)	(0.0575)	(41)	(0.035)	(175)	(0.019)	(97)
Chemicals	-0.0387	7,975	-0.310***	3,241	-0.0857	10,211	-0.0848**	7,857
	(0.0243)	(61)	(0.0912)	(23)	(0.0663)	(97)	(0.0333)	(63)
Cement	-0.880**	226	-0.475**	2,201	0.502**	5,687	0.248*	641
	(0.349)	(3)	(0.235)	(15)	(0.228)	(55)	(0.144)	(7)

Source: authors' compilation. Estimation method: Poisson Regression with conditional plant fixed effects. Standard errors in parenthesis, clustered by plant. Results are rounded to two decimals. "*", "**" and "***" represent significance at 10%, 5% and 1%, respectively. Sample size shows number of observations followed by number of plants (in parenthesis).