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Keywords Industrial energy intensity, innovation, energy price, carbon tax

JEL Classification O13, C33, Q41, Q55

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European Industrial Energy Intensity: The Role of Innovation 1995-2009

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Abstract

We investigate the direct role of technological innovation and other influencing factors on industry-level energy intensity based on a sample of 12 industries across 17 EU countries over 1995–2009. We develop an innovative industry-level patent dataset and find compelling evidence that patent stock negatively influences industrial energy intensity. Using a fixed effects estimator, we find a much stronger effect on energy-intensive industries with an estimated coefficient of -0.138 almost double that of less energy-intensive industries (estimated at -0.085). While our results show energy price remains the major determinant of energy intensity, the chemicals industry appears to be more susceptible to energy prices relative to other energy-intensive industries that are covered by the EU Emissions Trading Scheme (ETS). Our study reveals that asymmetric response of energy intensity to energy prices in which price rises between 2004 and 2008 accounts for more change in efficiency than when prices fall. We also explore regional differences, notably that carbon tax policy in Northern European countries, which began in the early 1990s, is responsible for a significant fraction of the decline in energy intensity in Northern Europe.

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1. Introduction

Energy efficiency is often seen as perhaps the most straightforward ‘no-regrets’ means of delivering energy security, greenhouse gas emissions reductions and decoupling economic growth from rising energy use (Jaffe, Newell & Stavins, 2004). Moreover, energy efficiency can act as a bulwark against ever-increasing pressure on energy-intensive industries to reduce emissions and energy use in a carbon-constrained world. Rising fuel prices and their impact on industrial competitiveness have made energy efficiency improvements a central focus of EU energy policy. The oil crises of 1973–1974 and 1979 brought energy prices (and hence energy efficiency) to the fore as a crucial concern in national policy-making. More recently, external pressures such as the US shale gas ‘revolution’ and China’s burgeoning steel exports have highlighted the challenges Europe faces in terms of global competitiveness if it is to retain its domestic manufacturing base. In response to a mandate from the European Council, the European Commission released a report on energy-intensive industries (like steel, ceramic, chemicals, glass), which documents how the competitiveness of these industries may be at risk as a result of increasing energy costs associated with energy prices and transmission costs (CEPS, 2014).

Faced with the slow recovery of the industrial output against the challenge of growing competitive pressures from emerging economies following the global financial crises, most countries in the EU continue to witness a falling share of their manufacturing sectors (Bernard et al, 2016; Stollinger, 2016). Given that the manufacturing sector is viewed as a key element in national industrial strategy and employment in traditional industries, many European politicians have sought to avert (or at least attenuate) the decline in manufacturing associated with the wider structural shift towards service sectors (Schettkat and Yocarini, 2006; OECD, 2016). These efforts have hinged on the presumption that a strong industrial base is fundamental to Europe’s economic recovery and competitiveness.

To remain profitable in such a globally competitive environment in the face of stringent environmental policies and regulation, firms must constantly increase their productivity performance. Becoming more innovative in term of production and process is one promising way to open new paths in this context. Since the launch of the EU ETS in 2005, there has been considerable debate over carbon leakage, i.e., the extent to which firms would move operations of higher-carbon activities abroad versus inducing European manufacturing firms to develop new emission reducing technological innovation and thereby maintain output levels (e.g, Sato et al, 2015; Demailly and Quirion, 2006).

Research into energy intensity, defined as the ratio of energy use to gross value added, has tended to focus on the contributions of energy efficiency improvements towards reducing global energy consumption and greenhouse emissions. Evidence of technological efficiency effect in decreasing aggregate energy intensity is documented in a number of studies, including Welsch and Ochsen (2005), Metcalf (2008), Zhang (2013), Voigt et al. (2014), Parker and Liddle (2016), and Karimu et al. (2017). Moreover, several previous studies also allude to the fact that structural effects can have an impact on the energy intensity change (see Unander, 2007; Lescaroux, 2008; Huntingdon, 2010; Mulder and de Groot, 2012; Mulder et al., 2014). This has necessitated using other perspectives beyond the traditional approach of technological and structural effects to further investigate the factors influencing energy efficiency. Investigating the factors contributing to declining energy intensity is usually based on regression analysis following decomposition of the total energy intensity into efficiency and structural effects.

However, while the technological efficiency effect and the structural effect separately affect aggregate energy intensity change, the existing literature reveals an obvious neglect of the direct role of technological innovation on energy intensity². Furthermore, even though technological efficiency

² Perhaps, this could be explained by lack of sector-level data on innovation activities such as patent in the manufacturing industry which has made its inclusion difficult in previous empirical studies (Anadon et al., 2011; Gallagher et al., 2012).

change is adjudged to be an important driver of the change in energy intensity, the index number approach does not account for the contribution coming from this source (Ma et al; 2009). To the extent that decomposition analyses provide important insights regarding the overall intensity of energy consumption, as well as the structure of the economy, sectoral energy intensity is directly linked with production, which tends to be impacted more specifically by policy actions.

We measure energy intensity by the ratio of energy use input to gross value added. Sectors also differ in terms of energy required relative to other inputs like capital and labour (Mulder and Groot, 2012). Therefore, gaining a comprehensive understanding of the factors influencing energy intensity (i.e., energy consumption per unit of output) at the sectoral level is crucial. Indeed, this analysis is all the more important considering the high degree of variation in energy intensity across industries, ranging from 40.70 TJ/ \$million PPP (in 1995\$) in the chemical industry to 1.87 TJ/ \$million PPP (in 1995\$) in the electrical and optical equipment industry³. For example, evidence of varying impact of technological innovation on energy intensity in different industries could indicate that certain industries possess greater or lesser ability to undertake more ambitious decarbonisation efforts and might require tailored intervention. This could provide useful information for policymakers on the design and implementation of fiscal incentives for enhancing further energy conservation and targeting new emission-reducing technologies.

We offer four main contributions in this study. First, we have developed a unique sector-level patent dataset to investigate the determinants of industrial energy intensity across European manufacturing industries. As such, patent stock provides insight into the interplay of energy prices and technological innovation on energy intensity. Second, building on the existing energy demand literature, we consider asymmetric response of industrial energy intensity to price by decomposing energy price into three components. Third, we explore heterogeneities across industry categories, with special

³ Average energy intensity is calculated by averaging the energy intensity across industry from 1995- 2009. See Appendix Figure 2 for the industrial energy intensity bar chart.

focus on energy-intensive industries and less energy-intensive industries. Further, subsectors of manufacturing differ in important respects from each other in term of intensity of energy use, hence their reasonable classification as energy-intensive and less energy-intensive industries. Finally, we compare regional industrial energy intensity analysis by accounting for inter-regional differences, notably the presence or absence of a carbon tax.

The remainder of the paper is structured as follows. In the next section, we provide a brief literature review of previous studies that examine the determinants of energy intensity. We describe our methodological approach in greater detail in Section 3. The data used are presented and discussed in Section 4. In Section 5 we present the results, while Section 6 offers some the conclusions and points to some important implications.

2. Literature review

Our study draws on two different strands of the academic literature that have each been well studied in their own right, but which have not intersected much – aggregate energy intensity found in single or multi-country version and asymmetric price response, usually employed in energy demand research. There is now a large body of work on energy intensity and its determinants, usually using a two-stage approach comprising index decomposition analysis technique and econometric techniques, on the relationship between energy intensity indices and their determinants⁴. These studies span a wide range of countries and time periods over the last three decades, including both multiple and single-country efforts. The change in energy intensity at the aggregate is found to occur through two basic sources. The change in sectoral energy productivity due to technological improvements, and

⁴ The two commonly used methods are the Fisher Ideal index, and the Logarithmic Mean Divisia Index (LMDI). See Ang and Zhang, 2000 for a detailed literature survey on index number decomposition analysis.

structural change which involves shifting production between sub-sectors, especially from energy-intensive manufacturing industries towards less energy-intensive service sectors.⁵

Many of the multi-country studies on economy-wide aggregate change in energy intensity analysis, including Oseni (2009), Zhang (2013), Jimenez and Mercado (2014), Mulder et al. (2014) and Atalla and Bean (2017), identify energy prices and per capita income as the main determinants of energy intensity. Examining energy determinants for 16 OECD countries, Oseni (2009) concludes that long-run reduction in energy intensity as a result of energy prices and income is largely due to movement away from energy-intensives activities and toward the less energy-intensive service sector. Drawing on 75 countries, Jimenez and Mercado (2014) show that per capita income, petroleum prices, fuel-energy mix, and GDP growth are the factors contributing to energy intensity with clear correlation with structural economic shift. They conclude that Latin American countries experience decline in energy intensity around 20% during the sample period which was regarded as underperformance. Atalla and Bean (2017) estimated the determinants of energy productivity in 39 countries and confirm that findings of higher levels of income per capita and higher energy prices are associated with greater energy productivity while a greater share of output from industry is associated with lower energy productivity levels.

Based on two-stage procedure, single country studies on economy-wide aggregate energy intensities include those of Metcalf (2008), Song and Zheng (2012) and Wu (2012) all of which find a marked reduction in energy intensity during the sample period and identified efficiency as the major driver responsible for decreasing energy intensity. Metcalf (2008) decomposed state-level energy intensity changes occurring in the United States and econometrically examined the decomposition indexes in

a panel analysis. In line with the earlier findings, Metcalf (2008) confirms that rising per capita income and energy prices significantly contribute to energy efficiency improvements but are not associated with structural economic shift. Using a provincial-level panel data set, Song and Zheng (2012) adopt an econometric approach to examine the driving forces behind China's changing energy intensity using a provincial-level panel data set for the period 1995 to 2009. They surmise that rising income plays a vital role in reducing energy intensity while increasing urbanization threatens energy intensity improvements. Wu (2012) further confirms that increasing income per capita and energy price led to a reduction in efficiency in China during over 1997–2007.

Sectoral studies include Lescaroux (2008) on the US manufacturing sector using two-digit SIC level data and Mulder (2014) on the determinants of energy intensity in the Dutch service sector. The common factor in all these studies is that price played an important role in explaining the decline in energy intensity. Zhang (2013) also shows that income growth and energy price increases were the main drivers of energy efficiency, while the impact of trade is positively related to energy intensity in the manufacturing sector in Eastern Europe. In contrast to the studies on the two-stage approach, Hang and Tu (2007), Fisher-Vanden et al. (2016) and Verbic et al., (2017) use only econometrics approach to investigate the determinants of energy intensity. In particular, Fisher-Vanden et al. (2016) considered four Chinese energy-intensive industries in examining the factors influencing energy intensity and concluded that in all four industries, energy prices and technology⁶ are significant contributors to the decline in energy intensity.

With respect to asymmetric price response, the energy demand literature has established that price changes may be asymmetric owing to the long life of capital and price-induced technical change (Gately and Huntington, 2002; Griffin and Schulman, 2005; Huntington, 2006; Adeyemi and Hunt

⁶ Fisher-Vanden et al. (2016) employ R&D expenditures as proxy for technological innovation. However, R&D is a measure of inputs, and takes no account of the productivity and effectiveness of effort (See Griffith et al., 2006).

2007, 2014; Olaniyan and Evans, 2014). It is therefore surprising that only a couple of papers, see Lescaroux (2008) and Parker and Liddle (2016), have attempted to examine this relationship between prices and efficiency. Lescaroux (2008) confirms the asymmetric response of energy intensity to prices, emphasizing that price rises is associated with more efficiency improvements than those lost when prices fall. However, Parker and Liddle (2016) find no statistically significant relationship between asymmetric price and energy intensity and conclude that the direction of price movement may not matter to energy intensity.

In summary, there is a broad agreement that increasing energy prices is an effective contributing tool for reducing energy intensity. Unlike Parker and Liddle (2016) who consider only upward and downward price movement, we adopt the traditional price decomposition approach following Adeyemi and Hunt (2007, 2014) and disaggregate energy price into three phases: price maximum (maximum historical prices), price recovery (sub-maximum increases) and price cut. This enables us to disentangle the effect of changing oil prices during the low-price period of prior to 2004 and the period of marked oil price increases over 2004-2008, which culminated in the historical high reached in July 2008 just before the onset of the Global Economic Crisis⁷. The interactions between technological innovation and the price components can lead to varying direct price-induced innovation in the manufacturing sector owing to the argument that the energy demand response to an increase in the maximum price is not necessarily the same as the response to a price recovery. Hence, understanding these interactions allows policymaker to revise policies to achieve their objectives as a result of price changes.

⁷ Although energy price includes all forms of energy other than oil, the emphasis on oil prices is only an indication of high volatility experienced by oil prices relative to other energy prices during the financial crises.

3. Methodology and Hypotheses

Our aim is to investigate the factors influencing energy intensity in the EU manufacturing sector. Many factors have been widely acknowledged to influence industrial energy intensity and the approach adopted here is similar to that of Fisher-Vanden et al (2016). We lay out below a set of relevant hypotheses to examine the impact of key economic factors in the EU manufacturing sector. These testable hypotheses are discussed under following general categories—energy prices; technological innovation; capital intensity; trade openness; regional differences; and exposure to carbon pricing.

The arguments as to why these determinants of energy intensity such as an increase in energy prices may lead to lower energy intensity has been well studied since higher prices are expected to lead to lower energy consumption (see Parker and Liddle; 2016, Mulder and Groot; 2012, 2014).

H1: We expect energy prices, ceteris paribus, to have a significant and negative relationship with energy intensity. In particular, we expect energy-intensive industries to respond more aggressively by lowering their energy intensity more than less energy-intensive industries in response to higher energy prices.

Closely allied to increases in energy prices is the impact of technological innovation on energy intensity. In practice, technical innovation in manufacturing industries might not be realized without an effective driving force in which pricing plays an important role. The increase in cost of energy could lead to the development of more energy-efficient technologies (Biroi and Keppler, 2000).

H2.1: New technological innovation potentially enhances higher output using the same level of inputs, thereby reducing energy intensity. We expect that technology improvements in specific processes and products, proxied by patent stock, will lead to a decline in energy intensity. Faced with the need to adopt low-carbon technologies, we also expect energy-intensive industries to generate, ceteris paribus, more patents, thereby leading to a greater impact in reducing energy than for less energy-intensive industries.

H2.2: The interplay between energy prices and innovation will result in substantial energy intensity reduction as firms are expected to react to an increase in energy prices by scaling up their investments in technological innovation. This interplay is proxied by the interaction of price and patent stock.

Capital accumulation of more energy-efficient capital stock due to new technology is also crucial to reducing energy intensity. Popp (2001) posits that firms made costly adjustments to capital, despite the fall in energy prices in the early 1980s, because the new technology, which was developed in response to the energy crisis, was better than the previously existing technology. Earlier studies, such as Thompson and Taylor (1995) and Steinbuks, and Neuhoff (2014) confirm the degree of substitution between energy and capital. Specifically, Thompson and Taylor (1995) established that capital and energy are substitutes in both the short and long run based on the estimates of the Morishima elasticity of substitution. Metcalf (2008) further argued that energy and technology may be substitutes in production. Thus, regardless of energy prices, technology-induced investment can contribute to reducing energy intensity.

H3: As a plausible means by which energy-efficient technologies can influence energy intensity, we expect capital intensity, proxied as capital-labour ratio, to be negatively related to energy intensity.

As more capital is geared toward more advanced production technologies, especially in energy-intensive industries, energy efficiency improves.

Trade openness has been considered as a channel for foreign technological spillovers in reducing energy consumption (Liao et al., 2009). This dates back to the work of Coe and Helpman (1995) which establish that technology spills over across countries via trade flows. Trade could also subject firms to a higher level of competition and encourage the development of cost-cutting strategies, which will encourage energy savings (EBRD, 2010). Technological diffusion via trade openness can stimulate domestic innovation and engender competition in the local economy, which also has implications for reducing energy intensity.

H4: Trade openness is expected to play an important role in explaining differences in energy intensity in the EU manufacturing sector. In more trade-exposed energy-intensive industries such as steel (basic metals), we expect a negative relationship with energy intensity in order for firms in the industries to remain competitive and maintain their market share in the international markets.

All 17 countries analyzed are part of the European Union and, as such, are subject to the same institutional framework, policies and directives (such as those on energy efficiency and climate change targets). We expect though that in addition to the expected national differences in how policies are implemented driven by national circumstance there may also be strong regional effects. There are clear groupings within the group of countries in terms of common history, level of development, industrial structure and policy approaches to energy and climate change. Over the course of the period of our study, the regulation of greenhouse gases has increased dramatically at both the national and EU level. In the early 1990s, Finland, followed by Sweden and Denmark imposed relatively high carbon taxes that have continued to this day. Following the Kyoto Protocol

in 1997, the EU instituted an EU-wide Emissions Trading Scheme (ETS), which applied to the power and some (but not all) of the manufacturing sector. The system began operations in 2005 with a trial period and a full-fledged system from 2008, near the end of our time horizon.

H5.1: We would expect there to be a clear negative relationship between the level of the carbon tax and energy intensity in those countries where a carbon tax has been employed.

H5.2: We expect that those sectors covered by the ETS will exhibit different responses in terms of improvements in energy intensity than other sectors that are not covered. In particular, we expect that energy-intensive sectors within the EU ETS (e.g., metals, pulp and paper) will have a lower price elasticity than those energy-intensive sectors not covered by the ETS (notably chemicals).

3.1 Panel data analysis

Our dataset is an unbalanced panel consisting of cross-sections of subsectors with a relatively short time series (15 years from 1995-2009). Given that the cross-sections cut across different subsectors in seventeen EU countries, there is the possibility of a range of time invariant country-specific and sector-specific unobserved factors influencing the behaviour of each sector. Hence, we adopt techniques from panel data econometrics, which are best suited to handle this observational-specific heterogeneity that is fixed over time. A distinctive feature of panel data modelling is the treatment of unobserved heterogeneity by simply including time-invariant unobservable individual effects in the model. The two alternative approaches for obtaining unbiased estimated parameters in panel data are to use fixed effects (FE) and random effects (RE) estimators, each of which treats unobserved heterogeneity differently in a model. While the FE estimator deals with such heterogeneity explicitly in the estimation process by putting in a dummy for each individual; otherwise known as the Least Squares Dummy Variables (LSDV) estimator, the RE estimator implicitly recognises it, and assumes the individual effects are drawn from the same probability distribution thereby making them random,

and treated as though they were a part of the error term. The FE estimator is always consistent, but the RE estimator, where applicable, is more efficient and becomes more parsimonious as it has fewer parameters. In a fixed effects model, consistency does not require that the individual and error terms are uncorrelated. However, RE estimators do require that the individual effects (and hence the composite error term) are uncorrelated with the explanatory variables for it to be consistent. A specification test based on the comparison of two alternative estimators of the same parameter vector is known as the Hausman test (Hausman, 1978), which is often used to choose the appropriate estimator.

However, since the cross-sections in this dataset represent in twelve industries in seventeen EU countries with distinctive sovereign power, these variations could amount to unobserved heterogeneity. If this unobserved heterogeneity was contained in variables indicative of factors such as climate change regulatory policy, it is highly likely that the unobserved heterogeneity, and hence the individual effects, would be correlated with the independent variables i.e. factors such as climate change regulatory policy could influence explanatory variables. In the event that the strict exogeneity assumption for a RE model is not tenable, only FE estimators would be consistent. We then proceed to investigate the factors influencing energy intensity of the EU manufacturing sector by employing a fixed-effect estimator while incorporating time dummies as controls for factors that are constant across sectors and countries but vary over time such energy prices. The model specification for the static fixed effects model for subsector energy intensity is as follows:⁸

$$EI_{it} = \beta_1 P_{it} + \beta_2 PAT_{it} + \beta_3 OPEN_{it} + \beta_4 Growth_{VAit} + \beta_5 K/L_{it} + \beta_6 Pat * Price_{it} + \delta_i D_t + \alpha_i + \varepsilon_{it} \quad (1)$$

⁸ Nevertheless, we use both estimators and carry out a Hausman test to select the specification that better suits our dataset.

where E_{it} it is log energy intensity, P_{it} is log energy price, PAT_{it} is log of patent stock, $Growth_{VAit}$ is the growth rate of value added, $OPEN_{it}$ is degree of trade openness, K/L_{it} is log of capital intensity, $Pat * Price_{it}$ is the interaction between patent stock and energy price. The α_i term is a fixed effect that allows for unobserved heterogeneity, D_t is the year dummy capturing any time effect while ε_{it} is the idiosyncratic random error.

3.2 Asymmetric price response

Past energy demand studies (see Dargay and Gately 1995; Gately and Huntington, 2002; Griffin and Schulman, 2005; and Huntington, 2006; Adeyemi and Hunt 2007, 2014; Olaniyan and Evans, 2014) have shown that energy prices have imperfect reversibility such that the responsiveness of demand in periods of high energy prices differs from the responsiveness in periods of falling prices. More importantly, these asymmetric price movements affect the level of technological change as higher prices tend to induce innovation or installation of more efficient capital stock which has important implications for energy intensity.

Drawing on these studies, we decompose energy prices into three different components to determine to examine the asymmetric response of energy price. Energy prices in this study (the log of real subsector prices) are decomposed into three categories which are price maximum (P_{max}), price cut (P_{cut}), and price recovery (P_{rec}), such that $P_t = P_1 + P_{max,t} + P_{cut,t} + P_{rec,t}$ where P_1 is the log of price in the initial year, $t = 1$; $P_{max,t}$ is the cumulative increase in log of maximum historical prices and is monotonically non-decreasing, i.e., $P_{max,t} \geq 0$. $P_{cut,t}$ cumulative decrease in log of prices; monotonically non-decreasing $P_{cut,t} \leq 0$; $P_{rec,t}$ cumulative sub-maximum increase in log of prices; monotonically non-decreasing: $P_{rec,t} \geq 0$. The fixed effects model in equation Eq (1) is generalised as follows;

$$EI_{it} = \beta_m P_{it}^m + \beta_c P_{it}^c + \beta_r P_{it}^r + \beta' X_{it} + \delta_i D_t + \alpha_i + \varepsilon_{it} \quad (2)$$

where El_{it} is the logarithm of the energy intensity for each subsector at time t , P_{it}^m is the logarithm of real price maximum for each subsector, P_{it}^r is the logarithm of real price recovery for each subsector while P_{it}^c is the logarithm of real price recovery for each subsector. α_i accounts for the fixed effects to capture heterogeneity across country and industries, D_t is a time dummy that accounts for specifications that change over time but that are constant across sectors, X_{it} are the covariates as defined in Eq (1) above, while D_t , α_i and ε_{it} remain as earlier defined.

4. Data Source and descriptive statistics

Our analysis is based on panel data from 12 manufacturing subsectors at the two -digit level using the International Standard of Industrial Classification (ISIC) Rev 3 for 17 European countries over the period 1995–2009. The selection of the 17 countries in our sample is determined mainly by data availability, especially by data on our main variable of interest, industry-level patent data. Together, these countries account for over 80% of EU GVA. The manufacturing subsectors covered by our study are reported in Table A1 in the Appendix, which shows the ISIC rev3 classification of the industries. We measure energy intensity by the ratio of energy use input to gross value added. The data series for sector-specific measures of output, investment and energy use are obtained from the World Input–Output Database (WIOD) ([Timmer et al., 2015](#)). The measure of output is value added, which is expressed in millions of national currencies at current prices, is extracted from the Socio-Economic Accounts section of the WIOD. The measure of output is value added in millions of national currencies, which we deflated using the sectorial price index of gross value added (where 1995 = 100). The constant value series are then converted to international prices using the purchasing power parity exchange rates from the Penn World Table (PWT7.1). Gross energy use, which is measured in physical units (TJ), is extracted from the Environmental Accounts section of the WIOD. Capital intensity is expressed as a ratio of capital to labour. Real fixed capital stock is measured in

1995 prices and converted to million 1995 international dollars in a manner analogous to output and labour is measured as number of people engaged in work (in thousands).

In the case of energy prices, previous studies (e.g. Sato and Dechezleprêtre, 2015; Parker and Liddle, 2016) have relied on country-level industrial energy prices published by the US Energy Information Agency (EIA). Following Adetutu et al (2016), we constructed industry-specific energy prices as a ratio of intermediate energy input expenditure at current purchasers' prices to gross energy use (in TJ). This approach provides a more robust measure of industrial energy prices faced by each industry. The intermediate energy input expenditure is also obtained from WIOD and then deflated to constant prices (where 1995 = 100) by applying the implicit price deflator for each subsector. The constant price series are then converted to international prices using the purchasing power parity exchange rates from the Penn World Table (PWT7.1).

The Patent variable include all patents granted by the European Patent Office over the study period. Past studies have lent credence to the superiority of patents to R&D as a potential proxy for innovation (see Popp, 2002, 2006; Ulku, 2007; Johnstone et al., 2010; Aghion et al., 2012). Patents granted are linked to industrial sectors using a concordance table between industries and technologies made available by the Fraunhofer Institute for System and Innovation Research. Instead of using patent flows as a measure of innovation, we constructed patent stocks for each country following an approach proposed by Heeley et al (2000), which confines the depreciation of the patent stock to a period lasting only several years. The approach also addresses the problem of calculating initial patent stock in the perpetual inventory approach. Similar to Blind and Jungmittag (2008), we assume a depreciation rate of 15% for the calculation of patent stocks and compute patent stocks as follows;

$$P_{nt} = \sum_{\tau=t-5}^t (1 - \mu)^{(t-\tau)} P_{nt}^{gr} \quad (3)$$

where P_{nt}^{gr} is the number of EPO patents granted to a given EU member state in country n in year t and μ is the depreciation rate. We interact patent stock with energy price in order to investigate the sectorial technological response to an increase in energy prices. We hypothesize that higher energy prices lead to the development of more energy-saving technologies thereby increasing innovative activities.

Trade openness for each subsector is measured as the ratio of the sum of imports and exports to output. Data for subsector exports and imports are accessed from the STAN database of the Organisation of Economic cooperation and Development (OECD). Exports and imports are available in millions of local currency units from *WIOD* before deflating by base year 1995 sector-specific implicit gross domestic deflators taken from the same database. The constant (real) local currency units were then converted to 1995 international dollars using purchasing power parity conversion from Penn World Tables. We also control for output growth, which is measured as the rate of change of value-added of each sub-sector using value-added data extracted from the *WIOD*. We control for capital intensity which is measured as a ratio of capital and labour.

Table 1 shows summary statistics for the levels of the key variables in 1995 across each country and Panel B presents the same for the changes through 2009. The ranking of countries looks sensible with Germany having the highest patent stock (2080), followed by France (893) and UK (500). All countries have experienced significant investment in technological innovations as indicated by the growth in the patent stock in column (4) of Panel B, with the exception being the UK that experienced negative change. On average, the patent stock increased from 279 in 1995 to 345 in 2009. Germany had the fastest absolute change in the patent stock, increasing by 682.

Table 1: Summary Statistics by Country

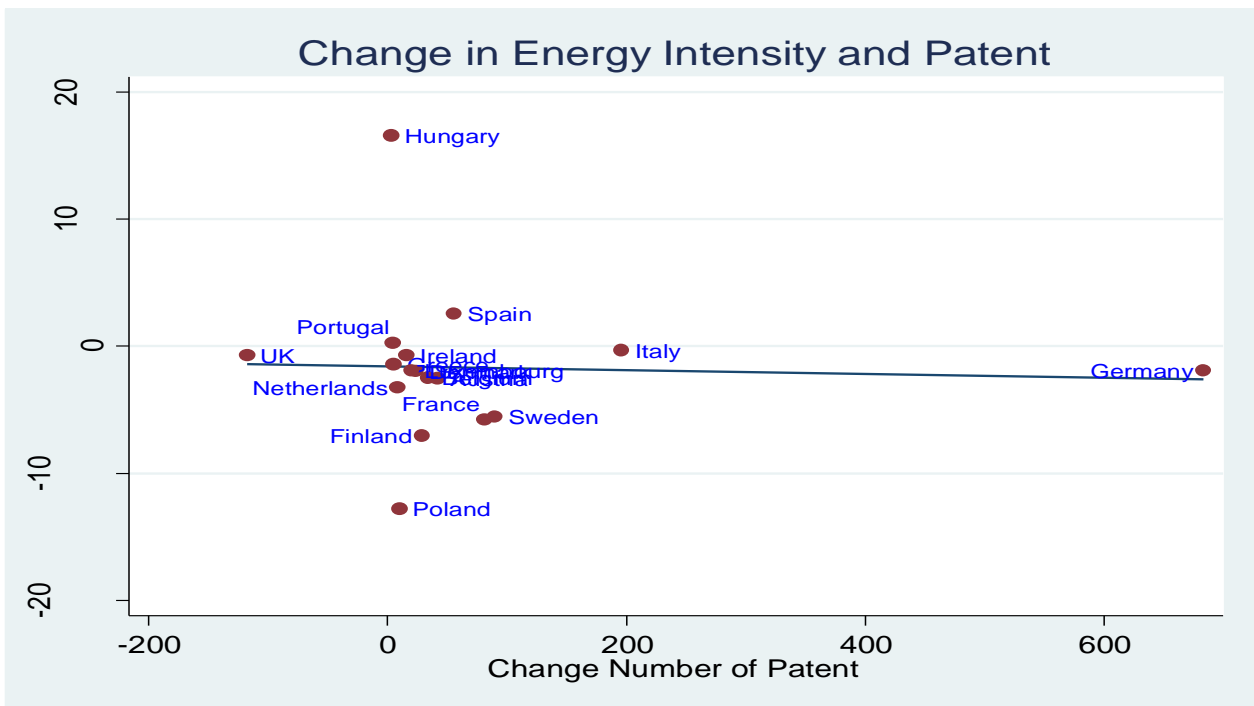
A: 1995 Levels Averaged by Country						
	Energy Intensity (TJ/\$M PPP)	ln (Value Added) (\$M PPP)	Total Price (\$MPPP/TJ)	Patent Stock (Number)	Trade Openness (ratio)	Share Gas & Electric (ratio)
Country	11.297	7.677	0.009	108.893	4.191	0.608
Denmark	12.216	7.773	0.012	94.472	7.016	0.552
Finland	8.775	6.903	0.004	65.890	6.011	0.537
France	21.258	7.078	0.006	93.807	3.117	0.315
Germany	13.142	9.219	0.014	893.734	3.100	0.614
Greece	9.581	10.015	0.010	2080.386	2.666	0.563
Hungary	11.272	6.801	0.015	1.627	2.532	0.285
Ireland	14.264	6.968	0.021	3.993	1.575	0.618
Italy	8.069	6.614	0.018	11.351	4.285	0.536
Luxembourg	9.103	9.735	0.015	290.701	1.622	0.654
Netherlands	12.423	4.738	0.007	13.348	0.000	0.645
Poland	15.604	7.966	0.011	363.801	6.201	0.677
Portugal	22.381	8.153	0.011	0.555	0.891	0.243
Spain	13.096	7.267	0.011	0.592	3.141	0.301
Sweden	9.014	8.993	0.016	31.836	2.457	0.481
United Kingdom	16.389	7.506	0.005	187.946	4.462	0.420
Mean	8.011	9.473	0.010	500.684	1.419	0.583
	12.701	7.832	0.011	279.036	3.233	0.507

B: Changes from 1995 to 2009 Averaged by Country

Country	Δ(Energy Intensity) (TJ/\$M PPP)	ln (Value Added) (\$M PPP)	Δ(Total Price) (\$MPPP/TJ)	Δ(Patent Stock) (Number)	Δ(Trade Openness) (ratio)	Δ(Share Gas & Electric) (ratio)
Austria	-2.532	0.257	0.006	41.523	1.786	0.034
Belgium	-2.463	0.094	0.008	34.165	10.028	0.063
Denmark	-1.976	-0.240	0.006	23.701	21.252	0.062
Finland	-7.018	0.301	0.006	29.211	1.421	0.106
France	-5.769	0.337	0.014	80.976	-3.100	0.013
Germany	-1.918	0.083	0.019	682.715	1.787	0.041
Greece	-1.385	0.032	0.009	4.992	1.643	0.144
Hungary	16.594	-0.491	-0.001	3.254	2.991	-0.063
Ireland	-0.696	0.344	0.002	15.899	1.889	-0.024
Italy	-0.299	-0.224	0.008	196.044	0.940	-0.004
Luxembourg	-1.934	0.337	0.008	20.004	20.847	-0.107
Netherlands	-3.243	0.083	0.010	7.950	6.550	-0.009
Poland	-12.792	0.471	0.016	9.688	-0.891	0.172
Portugal	0.242	0.107	0.004	4.511	-3.141	0.226
Spain	2.559	-0.057	0.001	55.722	-1.159	0.148
Sweden	-5.554	0.342	0.020	90.109	1.303	0.075
United Kingdom	-0.7285	-0.133	0.005	-117.767	0.381	0.031
Mean	-1.680	0.094	0.008	69.570	3.724	0.054

Poland has the most energy intensive countries and gained the largest efficiency improvement between 1995-2009 via reduction in energy intensity by over 57%. The mean energy intensity decreased by 8.4 % from 12.7 in 1995 to 11.021 in 2009. Hungary, Spain and Portugal witnessed an increase in energy intensity growth between 1995 and 2009. Appendix Table A3 also show similar cross-industry levels and growth in key variables.

Figure 1: Cross Country Variation in Growth of Energy Intensity and Patent Stock, 1995-2009



We also examine the correlation between energy intensity and patent stock by plotting bivariate scatter plots of growth in energy intensity and growth in patent stock for the 17 countries over the period 1995 – 2009. Figure 1 shows that change in energy intensity is negatively correlated with change in patent stock, with a correlation coefficient of -0.04 . The directions of the correlation is expected and it is somewhat indicative of the empirical support for the hypothesis that technology improvements in specific processes and products, proxied by patent stock, will lead to a decline in energy intensity. The figure also shows Germany, the technology giant that is often a future indicator for other nations in the European Union. Regardless of the correlation, one should exercise caution

in the interpretation of the outcomes due to the inability of correlation to determine cause and effect. The relationship is investigated more rigorously using econometric analysis.

5. Results and discussions

The estimation models specified in equations (1) and (2) are reported in Tables 2 to 6 for industrial energy intensity. We model both price symmetric and asymmetric response of energy intensity to energy prices.

Table 2: Estimation results for EU manufacturing sector

Variables	(1) Random effects	(2) Random effects	(3) Fixed effects	(4) Fixed effects
Total Price	-0.614*** (0.0241)		-0.607*** (0.0237)	
Price-max		-0.660*** (0.0295)		-0.737*** (0.0309)
Price-cut		-0.488*** (0.0403)		-0.465*** (0.0382)
Price-rec		-0.668*** (0.0316)		-0.620*** (0.0343)
Patent	-0.174*** (0.0282)	-0.0279** (0.0134)	-0.120*** (0.0304)	-0.0126 (0.0145)
Openness	0.0940*** (0.0238)	0.0955*** (0.0259)	0.244*** (0.0264)	0.206*** (0.0267)
Growth-VA	-0.389*** (0.0472)	-0.414*** (0.0468)	-0.355*** (0.0453)	-0.397*** (0.0441)
Capital-intensity	0.0804*** (0.0305)	0.0726** (0.0324)	-0.00803 (0.0333)	-0.0127 (0.0326)
Share-gas-electric	-0.321*** (0.0505)	-0.394*** (0.0504)	-0.298*** (0.0495)	-0.322*** (0.0482)
Patent*price	-0.0286*** (0.00518)		-0.0212*** (0.00515)	
Patent*price-max		-0.0333*** (0.00587)		-0.0231*** (0.00573)
Patent*price-cut		0.00696 (0.0105)		0.00546 (0.0101)
Patent*price-rec		-0.0225*** (0.00675)		-0.0146** (0.00660)
Constant	-2.274*** (0.392)	0.959** (0.408)	-4.268*** (0.433)	-0.611 (0.423)
Observations	2,197	2,197	2,197	2,197
R-squared			0.637	0.660
Year DVs	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

We estimate random effects and fixed effects estimators to avoid the potential bias associated with the pooled OLS due to the presence of unobservable sector-specific characteristics associated with panel data. In order to choose between the RE and FE estimators model, we conducted a Hausman (1978) test. The test statistic is based upon contrasting the FE and RE estimators in which the standard Hausman test rejects the null hypothesis that the conditional mean of the disturbances given the regressors is zero. Based on the statistical power of the test, the Hausman test suggests that fixed effects estimates are consistent. On this basis, we choose a fixed effects model as the appropriate model for our data and our subsequent analysis and discussions are premised on the fixed effect estimates in column (3) and (4) as reported in Table 2 and are used throughout the remainder of our study.

From column (3), we can see that, as expected, energy price has a negative and statistically significant relationship with industrial energy intensity. Holding everything else constant, the elasticity of -0.61 implies that a 1% higher energy price is associated with a 0.61% decline in energy intensity. Likewise, the impact of the patent stock is negative and statistically significant as is the interaction between the energy price and patent stock. Our results are consistent with the findings reported by Fisher-Vanden et al. (2016) for four Chinese energy-intensive industries. Energy efficiency is driven by patent stock through two key influences: (i) energy efficiency improvement due to technological innovations which is independent of the level of energy prices and (ii) technological innovation induced by raising energy prices. In addition, energy price is highly significant for the three price components in the asymmetric energy price specification (column 4). The asymmetric energy price model gives insight into the varying magnitude of the impact of shifting energy prices. Energy price maximum has the highest statistically significant impact on energy intensity with a price elasticity of -0.74, followed by price recovery, -0.62, while energy price cut, -0.47, experiences the lowest impact of the three

asymmetric price components. These findings indicate that the pattern of price movements is crucial in stimulating energy efficiency improvement as price rises led to more efficiency improvements than when efficiency gains when prices are low. These results are consistent with Lescaroux (2008) who provides a related evidence of asymmetric response of efficiency to energy prices in the US manufacturing sector but contrasts with those of Parker and Liddle (2016). The patent stock coefficient has the expected negative sign and is robust in the symmetric price model, although it is insignificant in the asymmetric price model.

Furthermore, the statistically significant coefficients of the interaction terms between patent and asymmetric price components indicates a higher reduction in energy intensity at the maximum energy price level, potentially due to adoption of more efficient energy substitute and development of technological innovation. On the contrary, the interaction term shows no significant impact on energy intensity at low prices as there is less incentive for process innovation to reduce energy use when energy prices are low. These findings are not surprising given the short panel framework of our data coupled with the relative persistent rising energy price during the sample period.

The impact of value-added growth rate on energy intensity is negative and robust across the model specifications. In line with other studies (see Jimenez and Mercado, 2014), our finding suggests that an increase in output level using the same level of fixed input tend to enhance energy efficiency. Although not quite robust, the result also shows that the coefficient of capital intensity is negatively associated with energy intensity. This implies that as stock of capital increases as a result accumulation of more energy efficient capital stock in relation to labour, energy intensity tends to decrease. Conversely, the result also shows that increases in international trade appears to raise energy intensity in the EU manufacturing sector. Zhang (2013) finds a similar result that energy intensity slightly increases with the increase in trade openness for the Eastern Europe transition

economies manufacturing sector. One reason adduced to the finding of positive relationship of trade openness and energy intensity stems from the hypothesis that trade induces specialization in more energy intensive industries. Also, the impact of state aids by EU member countries reinforces support for international competitiveness of these specialised trade exposed energy intensive sectors. We will expect that the higher the share of gas and electricity in the total energy use, the greater the corporate pressure to reduce prices⁹. Caelal and Dechezleprêtre (2016) report that fuel switching, shifting the fuel mix away from coal in favour of natural gas, has been responsible for the major share of the reduction in carbon dioxide emissions since the EU ETS was instituted in 2005. Overall, the estimates in Table 2 confirm that energy prices in general do play a crucial role in reducing energy intensity. It also reflects a pattern consistent with the notion that rising energy prices could directly engender energy efficiency as well as the indirect effect of stimulating energy-saving technology development and adoption.

Focusing on Table 3, we account for sectoral heterogeneities on the assumption that factors will affect industries differently owing to their variation in energy intensity and exposure to the Emission Trading Directive and other emission reduction obligations, such as carbon or energy taxes. To explore these heterogeneities, we first split of our sample into two subsamples i.e. energy-intensive and non-energy intensive industries. Building on existing literature (see Liddle, 2012; Sato and Dechezleprêtre, 2015; Song and Oh, 2015), we consider four energy-intensive industries: paper (ISIC 21-22), chemicals (ISIC 24), non-metallic products (ISIC 26), basic and fabricated metal (ISIC 27-28). The other eight industries are categorised as less-energy intensive manufacturing industries. The immediate striking difference between the fixed effects estimates of the energy-intensive and less energy-intensive sectors lies in the statistical significance of patent stock in both fixed effect models of energy-intensive industries as opposed to less-energy intensive industries where the patent stock

⁹ We expect different sectors to have different fuel mix given that different fuel mix drive responses such as investment. The reason we have to control fuel mix as well as heterogeneity.

coefficient is not statistically different from zero. The larger coefficients for the patent stock of the energy-intensive industries suggests that heavy industries rely more on innovation to reduce energy intensity compared with light industries. Energy price elasticities remain negative across the models and statistically significant for both industries, with less-intensive industries responding more to price increases than energy-intensive industries. Given the relative price sensitivity of the less-intensive industries, price increases account for more induced technological innovation in lighter manufacturing industries compared to energy-intensive industries. One possible explanation is that in less-intensive industries investments in energy-efficient technologies are driven largely by energy prices, while policies related to environmental concerns could be responsible for the propensity for innovation in energy-intensive industries. This finding implies that price elasticities of energy-intensive industries are more inelastic than those of less-intensive industries. Similar to the price decomposition estimates of the manufacturing industries reported in Table 2, the magnitude of the impact of price is seen to be highest at the maximum price level, followed by price-recovery while price-cut has the lowest price impact on energy intensity.

More often than not, industrial energy policies across different European countries are tailored to meet country-specific industrial strategies. For instance, in order to reduce CO₂ emissions, countries like Denmark, Finland, Sweden and Poland have unilaterally adopted of carbon tax dating back to the early 1990s¹⁰. A carbon tax policy is aimed at promoting substitution of fuel products and thereby encouraging energy saving as well as investment in energy efficiency improvement. Even for an EU-wide mechanism such as the ETS, in Phases I and II of the scheme (2005-7 and 2008-12), countries were allowed to set the allocation of individual allowances, allowing for considerable differences to arise. These inter-regional differences in climate change and energy policy will undoubtedly have an

¹⁰ The Nordic countries were the first countries to levy carbon taxes. Finland imposed a carbon tax in 1990; Norway and Sweden in 1991; and Denmark in 1992. Poland also imposed a carbon tax in 1990, which was (and remained) much lower than those in the Nordic countries (World Bank, 2016).

impact on regional energy consumption and regional energy intensity. Therefore, one way to possibly gain a more intuitive insight into geographical variation in energy intensity of European countries is

Table 3: Estimation result for manufacturing sector groups

Variables	Energy intensive industries	Less-Energy intensive industries		
	Fixed effect	Fixed effect	Fixed effect	Fixed effect
Total Price	-0.502*** (0.0343)		-0.669*** (0.0318)	
Price-max		-0.675*** (0.0573)		-0.855*** (0.0393)
Price-cut		-0.415*** (0.0641)		-0.499*** (0.0482)
Price-rec		-0.0856 (0.0857)		-0.704*** (0.0426)
Patent	-0.138** (0.0542)	-0.0921*** (0.0216)	-0.0848** (0.0375)	0.0249 (0.0197)
Openness	0.301*** (0.0380)	0.338*** (0.0375)	0.208*** (0.0349)	0.142*** (0.0356)
Growth-VA	-0.229*** (0.0686)	-0.285*** (0.0664)	-0.374*** (0.0578)	-0.419*** (0.0557)
Capital_intensity	0.0162 (0.0485)	0.0386 (0.0470)	-0.0245 (0.0435)	-0.0492 (0.0428)
Share-gas-electric	-0.452*** (0.0706)	-0.482*** (0.0684)	-0.191*** (0.0646)	-0.227*** (0.0622)
Patent*price	-0.0141* (0.00817)		-0.0215*** (0.00676)	
Patent*price-max		0.00385 (0.0130)		-0.0176** (0.00705)
Patent*price-cut		0.00520 (0.0178)		0.00728 (0.0125)
Patent*price-rec		-0.0861*** (0.0221)		-0.0101 (0.00823)
Constant	-3.746*** (0.640)	-1.469** (0.592)	-4.488*** (0.565)	-0.325 (0.561)
Observations	785	785	1,412	1,412
R-squared	0.628	0.657	0.660	0.689
Year DVs	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 4: Estimation results for regional groups

Variables	Western Fixed effect	Europe Fixed effect	Southern Fixed effect	Europe Fixed effect	Eastern Fixed effect	Europe Fixed effect	Northern Fixed effect	Europe Fixed effect
Total Price	-0.556*** (0.0371)		-0.594*** (0.0543)		-0.528*** (0.0472)		-0.429*** (0.0951)	
Price-max		-0.543*** (0.0486)		-0.694*** (0.0644)		-0.389*** (0.108)		-0.822*** (0.0936)
Price-cut		-0.774*** (0.0608)		-0.0366 (0.0651)		-0.674*** (0.128)		-1.409*** (0.207)
Price-rec		-0.678*** (0.0525)		-0.601*** (0.0618)		-0.336** (0.148)		-0.514*** (0.125)
Patent	-0.00410 (0.0458)	0.0697** (0.0297)	-0.280*** (0.0851)	-0.0650** (0.0290)	-0.469*** (0.0933)	0.0897** (0.0355)	-0.448*** (0.0873)	-0.185*** (0.0538)
Openness	0.313*** (0.0351)	0.247*** (0.0355)	0.332*** (0.0740)	0.415*** (0.0643)	-0.0405 (0.0996)	-0.0247 (0.103)	0.563*** (0.0699)	0.493*** (0.0641)
Growth-VA	-0.262*** (0.0619)	-0.266*** (0.0607)	-0.425*** (0.0957)	-0.437*** (0.0817)	-0.205 (0.128)	-0.121 (0.128)	-0.213** (0.103)	-0.291*** (0.0938)
Capital-intensity	-0.0630 (0.0464)	-0.0111 (0.0460)	-0.0919 (0.0871)	-0.0931 (0.0755)	-0.0343 (0.0756)	-0.0105 (0.0796)	0.0909 (0.0886)	0.0115 (0.0831)
Share-gas-electric	-0.148** (0.0633)	-0.108* (0.0628)	-0.299** (0.119)	-0.341*** (0.105)	-0.934*** (0.214)	-1.215*** (0.220)	-0.902*** (0.135)	-0.721*** (0.128)
Patent*total price	-0.0137* (0.00752)		-0.0510*** (0.0168)		-0.0988*** (0.0196)		-0.0515*** (0.0172)	
Patent*price-max		-0.0214** (0.00841)		-0.0907*** (0.0161)		-0.141*** (0.0339)		-0.00553 (0.0163)
Patent*price-cut		0.0662*** (0.0142)		-0.167*** (0.0224)		0.0660 (0.0558)		0.259*** (0.0440)
Patent*price-rec		-0.000281 (0.0100)		-0.0928*** (0.0169)		-0.154*** (0.0376)		0.0237 (0.0234)
Carbon-tax	-	-	-	-	-	-	-0.130*** (0.0342)	-0.144*** (0.0300)
Constant	-5.433*** (0.586)	-1.896*** (0.576)	-4.809*** (1.072)	-2.881*** (0.931)	1.199 (1.548)	3.227** (1.512)	-7.473*** (1.261)	-3.946*** (1.058)
Observations	1,108	1,108	493	493	200	200	396	396
R-squared	0.612	0.632	0.599	0.718	0.775	0.784	0.860	0.888
Year DVs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Fixed Effects

Yes

Yes

Yes

Yes

Yes

Yes

Yes

Yes

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

through regional analysis. We aggregate the 17 countries into four regions (Western Europe, Southern Europe, Eastern Europe and Northern Europe) to analyze any regional patterns while controlling for carbon tax¹¹.

No carbon tax estimate is reported in Table 4 for the other three regions as none of the countries in these regions introduced an effective carbon tax during the sample period.¹² Interestingly, the results show a negative and robust relationship between carbon tax and energy intensity in Northern Europe. Specifically, the carbon tax estimates of approximately -0.13 and -0.14 in both fixed effects models respectively for Northern Europe suggest that 1% increase in carbon tax will lead to 0.13% and 0.14% respectively in improvement of energy efficiency.

The comparison of the patent coefficients suggests a negative and statistically significant relationship with energy intensity across models in Northern and Southern Europe. The magnitude of the parameter estimates for the patent stock for Northern Europe is almost twice as large as the estimates of Southern Europe, possibly due to the existence of carbon tax which provides an incentive for induced innovation towards technologies that reduce emissions. A similar patent effect can be observed in Eastern Europe in the symmetric price model. Invariably, this underscores the assumption that environmental policies and regulations offer an important avenue for promoting technological innovation in the manufacturing sector. The picture is less clear-cut in the Western and Eastern European regions as the patent estimates have conflicting signs (although it is not significant for the price symmetric model in Western Europe).

¹¹ See Appendix Table A2 for the regional classification of the 17 sample countries.

¹² Technically, as Zyllicz (2013) explains, Poland does have a very small carbon tax of 0.24 PLN/t (0.06 euro/t) – roughly 1% of EU-ETS prices, which is well below the Pigouvian level understood as the level necessary to undertake the abatement at the socially justified (efficient) scale. Different countries in the three regions also had a range of other measures, for example, the UK created a ‘Climate Change Levy’, but this applied to all central generating plants and included nuclear power, which does not emit CO₂.

The coefficient of total energy price is negative and significantly affects energy intensity in all the groups as expected. We observe fairly large responses of energy intensity to price changes across each region, with Northern Europe having the lowest price effect on energy intensity in the price symmetric model. Compared with average price for the EU manufacturing sector, price elasticities for individual regions is lower than price elasticity of the full sample.

The absence of a carbon tax that would encourage energy efficiency improvement in Western and Southern Europe invariably feeds into the energy price estimates as it can be observed that the magnitude of price elasticities are slightly larger than in other regions. Furthermore, capital intensity is negatively associated with energy intensity in Western and Southern Europe. The finding is consistent with the non-significance of patent stock on energy intensity in the Southern European manufacturing sector. Moreover, it is not surprising that trade openness continues to have the same positive and robust effect on manufacturing sector energy intensity. Although in separating the data into four regions, we might have expected that net exporting regions with a positive trade balance might behave differently from other regions, the results show otherwise. Hence, the findings do not change in the face of regional heterogeneities. By contrast, trade openness seems to show a negative relationship with energy intensity in Eastern Europe where, possibly due to the impact of the market-oriented policy approach implemented in this region which facilitated trade inflow during the transition period from communism into market economies in the early 1990s.

We investigate whether the determining factors yield different impacts on energy intensity in some energy-intensive sectors that are exposed to emission reductions policy. We consider three major sectors; pulp & paper, non-metallic mineral products (e.g., construction materials, glass, ceramics, cement) and basic and fabricated metals, which are covered by the EU ETS and compare these sectors with the chemicals industry, which was not covered by the ETS during our sample period. Consistent

with our earlier findings, the fixed effect results presented in Table 5 shows that the coefficients of energy price are all negative and statistically significant in the price symmetric model. However, these subsectors have a lower price effect when compared with the price elasticity of the chemicals industry. This could partly be explained by these subsectors having internalised energy efficiency due to the emissions policy in place at the time, which would make energy intensity less responsive to energy price in these industries.

Table 5: Model estimations for ETS-covered industries

VARIABLES	ETS-covered Sectors				Non ETS-covered Sector			
	Paper		Non-Metallic		Basic Metal		Chemicals	
Price	-0.389*** (0.0422)		-0.351*** (0.0940)		-0.481*** (0.0842)		-0.680*** (0.0784)	
Price-max		-0.717*** (0.104)		-0.277* (0.148)		-1.020*** (0.153)		-0.844*** (0.102)
Price-cut		-0.183*** (0.0702)		-0.466*** (0.144)		-0.236 (0.195)		-1.316*** (0.197)
Price-rec		-0.0146 (0.117)		-0.213 (0.166)		0.563** (0.238)		-0.637*** (0.192)
Openness	0.313*** (0.0604)	0.322*** (0.0645)	0.579*** (0.0728)	0.544*** (0.0952)	-0.0432 (0.0846)	-0.00838 (0.0833)	0.822*** (0.0917)	0.762*** (0.0921)
Patent	0.0836 (0.0763)	-0.0393 (0.0338)	0.0308 (0.130)	0.0246 (0.0513)	0.0952 (0.120)	-0.0391 (0.0415)	-0.0817 (0.150)	0.118 (0.0738)
Growth-VA	-0.236* (0.123)	-0.223* (0.124)	-0.268** (0.113)	-0.279** (0.117)	-0.312** (0.145)	-0.386*** (0.139)	-0.175 (0.125)	-0.280** (0.126)
Capital-intensity	0.00414 (0.0849)	0.0267 (0.0897)	-0.428*** (0.0916)	-0.430*** (0.100)	0.0728 (0.0864)	0.132 (0.0845)	-0.188 (0.121)	-0.124 (0.119)
Share-gas-electric	-0.316*** (0.107)	-0.400*** (0.117)	-0.506*** (0.148)	-0.512*** (0.148)	-0.419** (0.165)	-0.436** (0.177)	-0.224* (0.118)	-0.290** (0.116)
Patent*price	0.0289** (0.0134)		-0.00177 (0.0202)		0.0310* (0.0183)		-0.0219 (0.0175)	
Patent*price-max		0.128*** (0.0345)		-0.0141 (0.0288)		0.128*** (0.0323)		0.0287 (0.0240)
Patent*price-cut		-0.0429* (0.0238)		0.0307 (0.0381)		-0.0194 (0.0411)		0.106** (0.0529)
Patent*price-rec		-0.0779** (0.0309)		-0.000185 (0.0397)		-0.189*** (0.0568)		-0.00307 (0.0508)
Constant	-3.851*** (0.967)	-2.236** (1.081)	-4.941*** (1.216)	-2.554** (1.280)	1.000 (1.415)	2.696** (1.238)	-12.31*** (1.688)	-8.373*** (1.484)
Observations	206	206	183	183	206	206	190	190
R-squared	0.575	0.609	0.667	0.681	0.698	0.732	0.850	0.865

Year DVs	YES	YES	YES	YES	YES	YES	YES	YES
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Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Similarly, for the price asymmetric model, reduction in energy intensity is also associated with price-max, as it is negative and robust across the three covered sectors, as well as in the chemicals industry. Unlike the average patent effect seen for the energy-intensive industries in Table 3, we cannot establish any significant impact on energy intensity from patent stock in either model. This also applies to the interaction of patent with energy maximum price, except for the non-metallic industry in asymmetric price model. However, since our sample only covers the first phase (2005-7) and two years out of the second phase (2008-12) of the ETS, this might be responsible for the lack of clear impact of technological innovation on these industries. Nevertheless, the asymmetric price model shows estimated coefficients of interaction terms between patent and price recovery for basic paper and metal industries appear to be significant. Again, the magnitude of the positive coefficient of trade openness for chemical industry further reinforces our earlier findings that trade induces specialization in more energy-intensive industries. Another notable observation is the statistical significance and negative effect on energy intensity of growth in value added growth rate and the share of gas and electricity. The statistical significance of the coefficients of both variables is clear across the four sectors, possibly as output expands in the face of fixed assets thereby ensuring optimal efficiency of energy use.

6. Conclusion

Energy intensity in the EU manufacturing sector has witnessed a substantial decline in energy intensity over last three decades. A great deal of debate about the determining factors of energy intensity has been centred on the decomposed energy efficiency indices as opposed to the direct effect of technological innovation. The implication of technological effects arising from the decomposition analysis is the tendency within each sector to reduce energy intensity, which does not necessarily imply adoption of more efficient technologies. Hence, we have focused on the direct impact of technology innovation instead of the broader concept of technological effects, which captures very

diverse drivers. We attempted to investigate the impact of several factors influencing energy intensity across 12 industries in 17 EU countries. To test our hypotheses, we use variables that captures these influencing factors, for instance, we use a unique industry-level patent data as a proxy for technological innovation. To the best of our knowledge, it is the first study that attempts to empirically analyze the direct role of technological innovation plays on energy intensity in the manufacturing sector using a unique industry-level patent data, which covers many EU countries.

We set out some testable hypotheses under the following categories - patent, energy prices, trade openness, capital intensity and carbon tax- to investigate the determinants of energy intensity across the EU manufacturing industries. The asymmetric response of industrial energy intensity to price via decomposition of energy price into three components was investigated. We also explore heterogeneities across industry categories, distinguishing between energy-intensive and less energy-intensive industries and examining regional differences in industrial energy intensity.

In tandem with our first hypothesis, energy price remains the major determinant of energy intensity in EU manufacturing sectors, although industries results show that energy intensity falls more in respond to higher price than less energy-intensive industries. The second hypothesis is also confirmed by our findings which show that patent stock seems to be consistently lead to a fall in overall industrial energy intensity, with a much stronger effect in energy-intensive industries with an estimated coefficient of -0.138 as opposed to less energy-intensive industries with an estimated parameter of -0.085. The result suggests that heavy industries rely more on innovation in reducing energy intensity compared with light industries. Technological innovation induced by rising energy prices, as measured by the patent and price interaction, is consistently associated with a decline in manufacturing energy intensity. In particular, the study shows that the decline in energy intensity is much more sensitive to maximum price changes than price cut, implying the evidence of asymmetric

response of efficiency to energy prices in which price rises between 2004 and 2008 of the sample period result in more efficiency improvements than when prices falls. We could not validate our third hypothesis as capital intensity do not seem to have any significant impact on energy intensity.

Although trade openness is generally believed to contribute to declining energy intensity in the EU owing to potential spillover effects as set out in our fourth hypothesis, our analysis indicates that energy intensity rises substantially with increased trade openness in the manufacturing sector. This increasing effect of trade openness on energy intensity is also observed across the industries.

Furthermore, our analysis of regional disparities indicates the implementation of a carbon tax has significantly reduced energy intensity in Northern Europe. Thus, there is a clear negative relationship between the level of the carbon tax and energy intensity in those countries where a carbon tax has been employed, which support our fifth hypothesis. The cumulative effect of carbon taxes over the years following its implementation in the Nordic countries in the early 1990s has caused energy intensity to fall by encouraging the adoption of low carbon and energy-saving technologies. Chemical industry seems to be more susceptible to energy prices relative to other ETS-covered energy-intensive industries which underscores the hypothesis that non ETS-covered covered has a lower price elasticity than those energy-intensive sectors covered by the ETS. In addition, the impact of patent stock also exhibits different outcome across regions, with negative impact on energy intensity established for only Southern Europe and Northern Europe which could be explained by different environmental and energy policy strategies each EU countries national government.

Overall, our study provides some policy implications for enhancing manufacturing energy efficiency in the EU region. First, technological innovation offers potential opportunities for the improvement of energy efficiency and development of new lower carbon-emission technologies, especially in the

energy-intensive industries. Second, the ETS policy facilitates efficiency improvement and offers a potential for reducing the susceptibility of energy-intensive industries to energy prices. Although, the policy could increase the risk of leakage as inefficient firms who should be responsive to energy price are being driven out of the market. Third, a complementarity of unilateral national carbon tax policy with EU ETS policy would play a crucial role in realising efficiency gains, especially across the Western European and Southern European countries. Third, the frequency of adjustments in climate change policy in line with changing global energy price will largely influence potential energy saving, for instance, in the less energy-intensive industries. Although the potential increase in energy intensity arising from international trade, government interventions in the form of state aids still exist in some of these sectors which could further weaken efficiency improvement effort or offset leakage that increases global emissions. Finally, governmental initiatives for energy conservation in the industrial sector that are meant to accelerate investments in clean technologies is recommended.

References

- Abrell, J. (2010). Regulating CO₂ emissions of transportation in Europe: A CGE-analysis using market-based instruments. *Transportation Research Part D: Transport and Environment* 15(4): 235-239.
- Adetutu, M.O., A.J. Glass, and T.G. Weyman-Jones. (2016). Decomposing energy demand across BRIIC countries. *Energy Economics* 54: 396-404.
- Adeyemi, O.I. and L.C. Hunt. (2007). Modelling OECD industrial energy demand: asymmetric price responses and energy-saving technical change. *Energy Economics* 29: 693–709.
- Adeyemi, O.I. and L.C. Hunt. (2014). Accounting for asymmetric price responses and underlying energy demand trends in OECD industrial energy demand. *Energy Economics*, 45: 435-444.
- Aghion, P., A. Dechezleprêtre, D. Hemous, R. Martin, R. and J. Van Reenen, (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy* 124(1): 1-51.

Anadon, L., Bunn, M., Chan, G., Chan, M., Jones, C., Kempener, R., Lee, A., Logar, N., Narayanamurti, V., 2011. Transforming U.S. energy innovation. Energy Technology Innovation Policy Research Group. Belfer Center for Social and International Affairs, Harvard Kennedy School, Cambridge, MA.

Atalla, T. and P. Bean, P (2017). Determinants of energy productivity in 39 countries: An empirical investigation. *Energy Economics* 62: 217-229.

Bernard, A.B., V. Smeets, and F. Warzynski. (2017). Rethinking deindustrialization. *Economic Policy*, 32(89): 5-38

Birol, F. and J.H. Keppler, (2000). Prices, technology development and the rebound effect. *Energy Policy*, 28(6-7): 457-469.

Blind, K. and A. Jungmittag. (2008). The impact of patents and standards on macroeconomic growth: a panel approach covering four countries and 12 sectors. *Journal of Productivity Analysis* 29(1): 51-60.

Boyd, G., J.F. McDonald, M. Ross, and D.A. Hanson. (1987). Separating the changing composition of US manufacturing production from energy efficiency improvements: a Divisia index approach. *The Energy Journal* 8(2): 77-96.

Boyd, G.A. and J.M. Roop. (2004). A note on the Fisher ideal index decomposition for structural change in energy intensity. *The Energy Journal* 25(1): 87-101.

Calel, R. and A. Dechezleprêtre. (2016). Environmental policy and directed technological change: evidence from the European carbon market. *Review of Economics and Statistics* 98(1): 173-191.

CEPS, (2014). Composition and Drivers of Energy Prices and Costs in Energy Intensive Industries: "The Case of Ceramics. *Flat Glass and Chemical Industries*", CEPS Special Report, Brussels.

Cornillie, J. and Fankhauser, S., (2004). The energy intensity of transition countries. *Energy Economics*, 26(3): 283-295.

Dargay, J.M. and D. Gately. (1995). The imperfect price-reversibility of non-transport oil demand in the OECD. *Energy Economics* 17(1): 59–71.

Demailly, D. and P. Quirion. (2006). CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation. *Climate Policy* 6(1): 93-113.

Diewert, W.E. (2001). The consumer price index and index number theory: a survey. *Department of Economics University of British Columbia, discussion paper 01, 2*.

EBRD (2010). Transition Report 2010: Recovery and Reform. Report of the Office of the Chief Economist, European Bank for Reconstruction and Development, London. Available on:

<http://www.ebrd.com/downloads/research/transition/tr10.pdf>

European Council. (2013). The European Council in 2013. Available on: <https://www.consilium.europa.eu/media/21303/qcao13001enc.pdf> (Accessed on 4 April 2018).

Fisher-Vanden, K., Y. Hu, G. Jefferson, M. Rock and M., Toman. (2016). Factors influencing energy intensity in four Chinese industries. *The Energy Journal* 37(1): 153 -178.

Gallagher, K.S., A. Grübler, L. Kuhl, G. Nemet and C. Wilson. (2012). The energy technology innovation system. *Annual Review of Environment and Resources* 37: 137-162.

Gately, D. and H.G. Huntington. (2002). The asymmetric effects of changes in price and income on energy and oil demand. *Energy Journal* 23(1): 19–55.

Griffin, J.M. and C.T., Schulman. (2005). Price asymmetry in energy demand models: a proxy for energy-saving technical change? *The Energy Journal* 26(1): 1–21.

Griffith, Rachel, Elena Huergo, Jacques Mairesse, and Bettina Peters. (2006). "Innovation and productivity across four European countries." *Oxford Review of Economic Policy* 22(4): 483-498.

Heeley M.B., A. Khorana, S.F. Matusik. (2000). Underpricing and the Long-run Financial Performance of IPOs: Information Asymmetry and Firm Incentive Capability. In: Reynolds D (ed.) *Frontiers of Entrepreneurship Research – Proceedings of the 19th Annual Entrepreneurship Research Conference 1999*, Babson College

Hausman, J.A. (1978). Specification tests in econometrics. *Econometrica* 46: 1251–1271.

Huntington, H.G. (2006). A note on price asymmetry as induced technical change. *Energy Journal* 27: 1–7.

Huntington, H.G. (2010). Structural change and U.S. energy use: recent patterns. *Energy Journal* 31: 25–39.

Jaffe, A. B., R.G. Newell, and R.N. Stavins, (2004). Economics of energy efficiency. *Encyclopedia of Energy* 2: 79-90.

Jimenez, R. and J. Mercado. (2014). Energy intensity: a decomposition and counterfactual exercise for Latin American countries. *Energy Economics* 42: 161-171.

Johnstone, N., I. Haščič, and D. Popp, D. (2010). Renewable energy policies and technological innovation: evidence based on patent counts. *Environmental and Resource Economics* 45(1): 133-155.

Karimu, A., R. Brännlund, T. Lundgren, and P. Söderholm. (2017). Energy intensity and convergence in Swedish industry: A combined econometric and decomposition analysis. *Energy Economics* 62: 347-356.

- Lescaroux, F. (2008). Decomposition of US manufacturing energy intensity and elasticities of components with respect to energy prices. *Energy Economics* 30: 1068–1080.
- Liddle, B. (2010). Revisiting world energy intensity convergence for regional differences. *Applied Energy* 87: 3218–3225
- Liddle, B. (2012). The importance of energy quality in energy intensive manufacturing: Evidence from panel cointegration and panel FMOLS. *Energy Economics* 34(6): 1819-1825.
- Ma, C. and D.L. Stern (2008). China's changing energy intensity trend: a decomposition analysis. *Energy Economics* 30: 1037–1053.
- Ma, H., L. Oxley, and J. Gibson. (2009). Substitution possibilities and determinants of energy intensity for China. *Energy Policy* 37(5): 1793-1804.
- Ma, C. and D.I. Stern. (2008). China's changing energy intensity trend: A decomposition analysis. *Energy Economics* 30(3): 1037-1053.
- Marrero, G.A. and F.J., Ramos-Real. (2013). Activity sectors and energy intensity: decomposition analysis and policy implications for European countries (1991–2005). *Energies* 6: 2521–2540.
- Metcalf, G.E. (2008). An empirical analysis of energy intensity and its determinants at the state level. *The Energy Journal* 29(3): 1-26.
- Mulder, P. (2015). International specialization, sector structure and the evolution of manufacturing energy intensity in OECD countries. *The Energy Journal* 36(3): 111-136.
- Mulder, P. and H.L.F. de Groot. (2011). Energy productivity performance across 14 OECD countries: the role of energy-extensive sectors. In: Florax, R.J.G.M., De Groot, H.L.F., Mulder, P. (Eds.), *Improving Energy Efficiency Through Technology: Trends, Investment Behaviour and Policy Design*. Edward Elgar, Cheltenham, Glos, UK.
- Mulder, P. and H.L.F. de Groot. (2012). Structural change and convergence of energy intensity across OECD countries, 1970–2005. *Energy Economics* 34: 1910–1921.
- Mulder, P., de Groot, H.L.F., Pfeiffer, B., 2014. Dynamics and determinants of energy intensity in the service sector: a cross-country analysis, 1980–2005. *Ecological Economics* 100: 1–15.
- OECD, 2011. STAN Industry Rev. 3, 2008, STAN: OECD Structural Analysis Statistics (database)
- Olaniyan, M.J. and J. Evans. (2014). The importance of engaging residential energy customers' hearts and minds. *Energy Policy* 69: 273-284.
- Oseni, M.O. (2009). Analysis of energy intensity and its determinants in 16 OECD countries. *Journal of Energy and Development* 35(1/2): 101-140.
- Parker, S. and B. Liddle. (2016). Energy efficiency in the manufacturing sector of the OECD: Analysis of price elasticities. *Energy Economics* 58: 38-45.

- Petrick, S. and Wagner, U., 2014. *The impact of carbon trading on industry: Evidence from German manufacturing firms* (No. 1912). Kiel Institute for the World Economy (IfW).
- Popp, D.C. (2001). The effect of new technology on energy consumption. *Resource and Energy Economics*, 23(3): 215-239.
- Popp, D. (2006). International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management* 51(1): 46-71.
- Sato, M. and A. Dechezleprêtre. (2015). Asymmetric industrial energy prices and international trade. *Energy Economics* 52: S130-S141.
- Sato, M., K. Neuhoff, V. Graichen, K. Schumacher and F. Matthes. (2015). Sectors under scrutiny: evaluation of indicators to assess the risk of carbon leakage in the UK and Germany. *Environmental and Resource Economics* 60(1): 99-124.
- Schmoch, U., F. Laville, P. Patel. and R. Frietsch. (2003). Linking technology areas to industrial sectors. *Final Report to the European Commission, DG Research, 1(0)*, p.100.
- Shahiduzzaman, M. and K. Alam. (2013). Changes in energy efficiency in Australia: a decomposition of aggregate energy intensity using logarithmic mean Divisia approach. *Energy Policy* 56: 341–351.
- Steinbuks, J., and K. Neuhoff. (2014). Assessing energy price induced improvements in efficiency of capital in OECD manufacturing industries. *Journal of Environmental Economics and Management* 68(2): 340-356.
- Sue Wing, I. (2008). Explaining the declining energy intensity of the U.S. economy. *Resource and Energy Economics* 30(1): 21–49.
- Song, C. and W. Oh. (2015). Determinants of innovation in energy intensive industry and implications for energy policy. *Energy Policy* 81: 122-130.
- Stöllinger, R., (2016). Structural change and global value chains in the EU. *Empirical Journal of European Economics* 43(4): 801-829
- Timmer, M.P., E. Dietzenbacher, B. Los, R. Stehrer, and G.J. Vries. (2015). An illustrated user guide to the world input–output database: the case of global automotive production. *Review of International Economics*, 23(3): 575-605.
- Ulku, H. (2007). R&D, innovation, and growth: evidence from four manufacturing sectors in OECD countries. *Oxford Economic Papers* 59(3): 513-535.
- Unander, F. (2007). Decomposition of manufacturing energy-use in IEA countries: how do recent developments compare with historical long-term trends? *Applied Energy* 84: 771–780.

- Van Looy, B., C. Vereyden and U. Schmoch. (2014). Patent Statistics: Concordance IPC V8–NACE Rev. 2. *Eurostat, European Commission, Luxembourg*.
- Voigt, S., E. De Cian, M. Schymura, and E. Verdolini. (2014). Energy intensity developments in 40 major economies: structural change or technology improvement? *Energy Economics* 41: 47–62.
- Welsch, H., and C. Ochs. (2005). The determinants of aggregate energy use in West Germany: factor substitution, technological change, and trade." *Energy Economics* 27(1): 93-111.
- Wan, J., K. Baylis, and P. Mulder. (2015). Trade-facilitated technology spillovers in energy productivity convergence processes across EU countries. *Energy Economics* 48: 253–264.
- World Bank, Ecofys, and Vivid Economics. (2016). *State and Trends of Carbon Pricing 2016*. Washington, DC: World Bank. <https://openknowledge.worldbank.org/handle/10986/25160> License: CC BY 3.0 IGO
- Wu, Y. (2012). Energy intensity and its determinants in China's regional economies. *Energy Policy* 41: 703–711
- Zhang, F. (2013). The energy transition of the transition economies: An empirical analysis. *Energy Economics*, 40: 679-686.
- Zylicz, T., 2013. Choosing efficient combinations of policy instruments for low-carbon development and innovation to achieve Europe's 2050 climate targets. Country report: Poland. Cecilia 2050 Optimal EU Climate Policy. Available on https://cecilia2050.eu/system/files/%C5%BBylicz%20%282013%29_Country%20Report%20-%20Poland.pdf

Appendix

Table A1: Sectoral classification

Industry	ISIC rev3
Food, beverages and tobacco	15-16
Textiles and textile	17-18
Leather, leather products and footwear	19
Wood and of wood and cork	20
Pulp, paper, paper, printing and publishing	21-22
Chemicals and chemical	24
Rubber and plastics	25
Other non-metallic mineral	26
Basic metals and fabricated metal	27-28
Machinery, nec	29
Electrical and optical equipment	30-33
Transport equipment	34-35

Table A2: Regional classification of Countries

Western Europe	Southern Europe	Eastern Europe	Northern Europe
Austria	Greece	Hungary	Denmark
Belgium	Italy	Poland	Finland
France	Portugal		Sweden
Germany	Spain		
Ireland			
Luxembourg			
Netherlands			
United Kingdom			

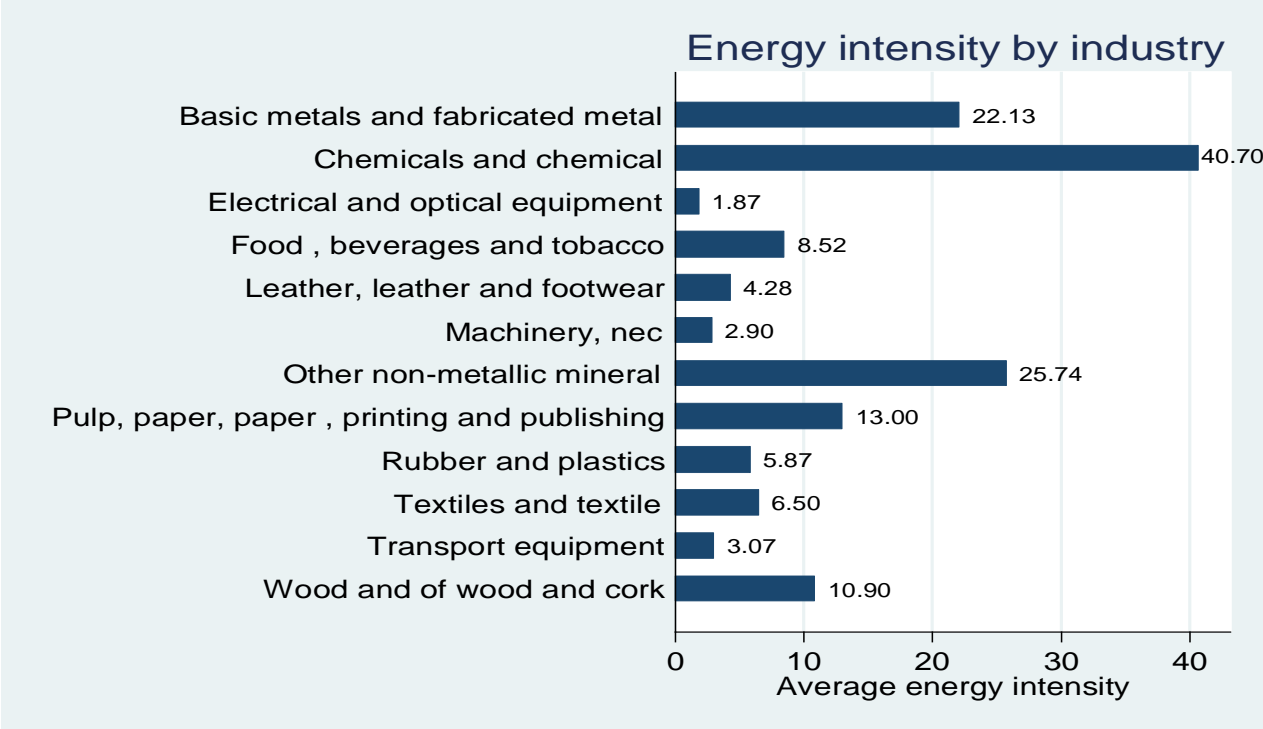
Table A3: Summary Statistics by Industry**Table A3: Summary Statistics by Industry****A: 1995 Levels Averaged by Industry**

Industry	Energy Intensity (TJ/\$M PPP)	ln (Value Added) (\$M PPP)	Total Price (\$MPPP/TJ)	Patent Stock (Number)	Trade Openness (ratio)	Capital Intensity (\$PPP/No employees)	Share Gas & Elect (ratio)
Food, beverages and tobacco	7.841	8.700	0.009	50.504	1.861	4.466	0.526
Textiles and textile	7.419	7.693	0.013	100.147	4.244	3.864	0.558
Leather, leather and footwear	4.321	5.960	0.017	6.238	6.613	3.706	0.534
Wood and of wood and cork	10.682	6.896	0.010	70.549	1.813	3.923	0.402
Pulp, paper, paper, printing and publishing	12.024	8.324	0.009	106.281	1.434	4.301	0.554
Chemicals and chemical	41.294	8.374	0.003	465.055	3.367	4.926	0.326
Rubber and plastics	5.171	7.485	0.019	146.971	2.500	4.306	0.716
Other non-metallic mineral	27.410	7.701	0.005	154.932	1.106	4.572	0.410
Basic metals and fabricated metal	26.570	8.576	0.005	239.731	2.236	4.265	0.367
Machinery, nec	3.271	8.161	0.015	868.279	3.440	3.980	0.514
Electrical and optical equipment	2.274	8.270	0.018	867.574	4.812	4.088	0.578
Transport equipment	3.641	7.730	0.016	272.174	5.563	4.263	0.602

B: Changes from 1995 to 2009 Averaged by Industry

Industry	Δ(Energy Intensity) (TJ/\$M PPP)	Δln(Value Added) (\$M PPP)	Δ(Total Price) (\$MPPP/TJ)	Δ(Patent Stock) (Number)	Δ(Trade Openness) (ratio)	Δ(Capital Intensity) (\$PPP/No employees)	Δ(Share Gas & Elect) (ratio)
Food, beverages and tobacco	0.492	-0.028	0.004	13.285	0.948	0.001	0.120
Textiles and textile	-2.429	-0.410	0.010	3.054	4.499	0.042	0.112
Leather, leather and footwear	-1.063	-0.575	0.005	-0.313	22.448	0.629	0.075
Wood and of wood and cork	1.399	0.085	-0.001	13.807	0.560	0.931	-0.068
Pulp, paper, paper, printing and publishing	0.716	0.150	0.006	5.716	0.380	0.207	-0.012
Chemicals and chemical	-3.675	0.343	0.008	-75.587	3.402	0.312	0.084
Rubber and plastics	0.714	0.220	0.009	46.485	0.903	0.179	0.033
Other non-metallic mineral	-4.027	-0.013	0.003	-5.298	0.394	0.248	0.071
Basic metals and fabricated metal	-9.714	0.118	0.004	41.186	0.510	0.163	0.127
Machinery, nec	-1.147	0.252	0.011	236.208	0.718	-0.033	0.041
Electrical and optical equipment	-0.330	0.600	0.029	354.390	3.063	0.058	0.019
Transport equipment	-1.028	0.312	0.009	201.912	9.062	0.305	0.052

Figure A1: Industrial energy intensity averaged by industry from 1995-2009



Robustness checks

We check the robustness of our results by investigating whether the results do not change when we remove the 2009 sample from our dataset. This is informed by the need to make sure that our results are not driven by the sudden fall in oil price in 2009. We experimented by estimating our models using a sample period spanning 2005-2008.

Table A4: Estimation results for EU manufacturing sector, 1995-2008

Variables	Random effect model	Random effect model	Fixed effect model	Fixed effect model
Total Price	-0.602*** (0.0242)		-0.594*** (0.0239)	
Price-max		-0.652*** (0.0296)		-0.737*** (0.0308)
Price-cut		-0.451*** (0.0411)		-0.425*** (0.0391)
Price-rec		-0.647*** (0.0318)		-0.581*** (0.0347)
Patent	-0.178*** (0.0281)	-0.0301** (0.0134)	-0.124*** (0.0303)	-0.0139 (0.0145)
Openness	0.0855*** (0.0240)	0.0860*** (0.0262)	0.236*** (0.0268)	0.197*** (0.0271)
Growth_VA	-0.378*** (0.0485)	-0.388*** (0.0477)	-0.340*** (0.0466)	-0.369*** (0.0450)
Capital_intensity	0.105*** (0.0311)	0.0997*** (0.0330)	0.0180 (0.0341)	0.0177 (0.0333)
Share-gas_electric	-0.324*** (0.0508)	-0.388*** (0.0505)	-0.303*** (0.0499)	-0.322*** (0.0483)
Patent*price	-0.0291*** (0.00516)		-0.0220*** (0.00513)	
Patent*price-max		-0.0348*** (0.00584)		-0.0239*** (0.00570)
Patent*price-cut		0.00269 (0.0106)		0.00243 (0.0101)
Patent*price-rec		-0.0247*** (0.00672)		-0.0164** (0.00657)
Constant	-2.115*** (0.399)	1.029** (0.415)	-4.140*** (0.442)	-0.601 (0.431)
Observations	2,164	2,164	2,164	2,164
R-squared	0.648	0.621	0.629	0.655
Year DVs	YES	YES	YES	YES
Fixed Effects	YES	YES	YES	YES

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

We found the estimated parameters for both symmetric and asymmetric price models to be very similar to those with full sample period used for the paper. We also estimated our model for both energy intensive and less-energy intensive industries, and the regions the 1995–2008 sample period. We obtained quite similar results to the earlier analysis. The results are reported from Table A4 to Table A7. Alternatively, we specify another model in which lag variables were included in the model but the results are not reported supported.

Table A5: Estimation result for industry groups, 1995-2008

Variables	Energy intensive industries		Less-Energy intensive industries	
	Fixed effects	Fixed effects	Fixed effects	Fixed effects
Total Price	-0.503*** (0.0347)		-0.651*** (0.0321)	industries
Price-max		-0.681*** (0.0582)		-0.855*** (0.0392)
Price-cut		-0.424*** (0.0648)		-0.451*** (0.0492)
Price-rec		-0.0528 (0.0895)		-0.656*** (0.0430)
Patent	-0.138** (0.0549)	-0.0949*** (0.0220)	-0.0921** (0.0374)	0.0219 (0.0195)
Openness	0.297*** (0.0395)	0.341*** (0.0391)	0.201*** (0.0352)	0.134*** (0.0358)
Growth_VA	-0.241*** (0.0702)	-0.278*** (0.0679)	-0.350*** (0.0595)	-0.377*** (0.0568)
Capital_intensity	0.0151 (0.0507)	0.0363 (0.0492)	0.00897 (0.0444)	-0.0118 (0.0435)
Share-gas-electric	-0.440*** (0.0716)	-0.474*** (0.0693)	-0.207*** (0.0650)	-0.237*** (0.0621)
Patent*price	-0.0138* (0.00825)		-0.0227*** (0.00673)	
Patent*price-max		0.00584 (0.0132)		-0.0189*** (0.00699)
Patent*price-cut		0.00646 (0.0179)		0.00372 (0.0125)
Patent*price-rec		-0.0887*** (0.0225)		-0.0122 (0.00816)
Constant	-3.661*** (0.673)	-1.487** (0.625)	-4.355*** (0.573)	-0.368 (0.565)
Observations	773	773	1,391	1,391
R-squared	0.617	0.648	0.651	0.686
Year DVs	YES	YES	YES	YES
Fixed Effects	YES	YES	YES	YES

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A6: Estimation results for regional groups, 1995-2008

Variables	Western Europe		Southern Europe		Eastern Europe		Northern Europe	
	Fixed effects	Fixed effects	Fixed effects	Fixed effects	Fixed effects	Fixed effects	Fixed effects	Fixed effects
Total Price	-0.527*** (0.0383)		-0.580*** (0.0541)		-0.528*** (0.0472)		-0.429*** (0.0951)	
Price_Max		-0.539*** (0.0495)		-0.712*** (0.0640)		-0.389*** (0.108)		-0.822*** (0.0936)
Price_Cut		-0.729*** (0.0642)		0.0130 (0.0642)		-0.674*** (0.128)		-1.409*** (0.207)
Price_Rec		-0.646*** (0.0541)		-0.557*** (0.0617)		-0.336** (0.148)		-0.514*** (0.125)
Patent	-0.0394 (0.0466)	0.0550* (0.0303)	-0.221*** (0.0843)	-0.0557* (0.0285)	-0.469*** (0.0933)	0.0897** (0.0355)	-0.448*** (0.0873)	-0.185*** (0.0538)
Openness	0.306*** (0.0362)	0.245*** (0.0364)	0.301*** (0.0779)	0.351*** (0.0673)	-0.0405 (0.0996)	-0.0247 (0.103)	0.563*** (0.0699)	0.493*** (0.0641)
Growth_VA	-0.261*** (0.0643)	-0.249*** (0.0630)	-0.407*** (0.0995)	-0.360*** (0.0834)	-0.205 (0.128)	-0.121 (0.128)	-0.213** (0.103)	-0.291*** (0.0938)
Capital_intensity	-0.0438 (0.0488)	0.0110 (0.0484)	0.00326 (0.0913)	0.0276 (0.0780)	-0.0343 (0.0756)	-0.0105 (0.0796)	0.0909 (0.0886)	0.0115 (0.0831)
Share_gas_electric	-0.113* (0.0645)	-0.0908 (0.0638)	-0.363*** (0.120)	-0.332*** (0.104)	-0.934*** (0.214)	-1.215*** (0.220)	-0.902*** (0.135)	-0.721*** (0.128)
Patent*price	-0.0172** (0.00761)		-0.0420** (0.0167)		-0.0988*** (0.0196)		-0.0515*** (0.0172)	
Patent*price-max		-0.0233*** (0.00850)		-0.0780*** (0.0159)		-0.141*** (0.0339)		-0.00553 (0.0163)
Patent*price-cut		0.0622*** (0.0146)		-0.169*** (0.0217)		0.0660 (0.0558)		0.259*** (0.0440)
Patent*price-rec		-0.00446 (0.0104)		-0.0810*** (0.0165)		-0.154*** (0.0376)		0.0237 (0.0234)
Carbon_Tax	-	-	-	-	-	-	-0.130*** (0.0342)	-0.144*** (0.0300)
Constant	-5.142*** (0.603)	-1.857*** (0.588)	-4.755*** (1.114)	-2.684*** (0.983)	1.199 (1.548)	3.227** (1.512)	-7.473*** (1.261)	-3.946*** (1.058)
Observations	1,086	1,086	482	482	200	200	396	396
R-squared	0.600	0.622	0.567	0.706	0.775	0.784	0.860	0.888
Year DVs	YES	YES	YES	YES	YES	YES	YES	YES

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A7: Estimations results for ETS-covered industries, 1995-2008

VARIABLES	ETS-covered Sectors				Non ETS- covered Sector			
	Paper		Non-Metallic		Basic Metal		Chemicals	
Total Price	-0.388*** (0.0425)		-0.358*** (0.0966)		-0.480*** (0.0847)		-0.662*** (0.0822)	
Price_Max		-0.723*** (0.105)		-0.311** (0.151)		-1.025*** (0.155)		-0.859*** (0.100)
Price_Cut		-0.180** (0.0711)		-0.501*** (0.148)		-0.233 (0.197)		-1.339*** (0.196)
Price_Rec		-0.0176 (0.117)		-0.182 (0.168)		0.557** (0.241)		-0.366* (0.220)
Patent	0.0919 (0.0775)	-0.0353 (0.0347)	0.0486 (0.133)	0.0446 (0.0541)	0.108 (0.120)	-0.0421 (0.0419)	-0.0828 (0.152)	0.158** (0.0719)
Openness	0.305*** (0.0625)	0.310*** (0.0669)	0.588*** (0.0742)	0.550*** (0.0961)	-0.0410 (0.0881)	0.00461 (0.0873)	0.848*** (0.0928)	0.807*** (0.0895)
Growth_VA	-0.239* (0.124)	-0.230* (0.125)	-0.279** (0.115)	-0.294** (0.118)	-0.319** (0.146)	-0.379*** (0.140)	-0.146 (0.134)	-0.214* (0.127)
Capital_intensity	0.00336 (0.0893)	0.0238 (0.0961)	-0.417*** (0.0939)	-0.411*** (0.101)	0.0519 (0.0908)	0.134 (0.0901)	-0.249* (0.132)	-0.273** (0.125)
Share-gas-electric	-0.299*** (0.110)	-0.385*** (0.119)	-0.494*** (0.151)	-0.484*** (0.150)	-0.416** (0.166)	-0.421** (0.179)		
Patent*price	0.0300** (0.0136)		-0.000526 (0.0205)		0.0334* (0.0184)		-0.0258 (0.0179)	
Patent*price-max		0.130*** (0.0353)		-0.00289 (0.0301)		0.129*** (0.0325)		0.0413* (0.0238)
Patent*price-cut		-0.0422* (0.0241)		0.0340 (0.0384)		-0.0196 (0.0413)		0.101* (0.0516)
Patent*price-rec		-0.0777** (0.0311)		-0.00232 (0.0398)		-0.188*** (0.0573)		-0.0363 (0.0522)
Constant	-3.779*** (0.990)	-2.107* (1.114)	-5.217*** (1.300)	-2.843** (1.327)	1.268 (1.524)	2.681* (1.365)	-12.27*** (1.680)	-8.393*** (1.416)
Observations	203	203	180	180	203	203	187	187
R-squared	0.559	0.595	0.662	0.679	0.676	0.711	0.848	0.871
Year DVs	YES	YES	YES	YES	YES	YES	YES	YES

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Figure A2: Time Series of Energy Intensity and Energy Price by Industry

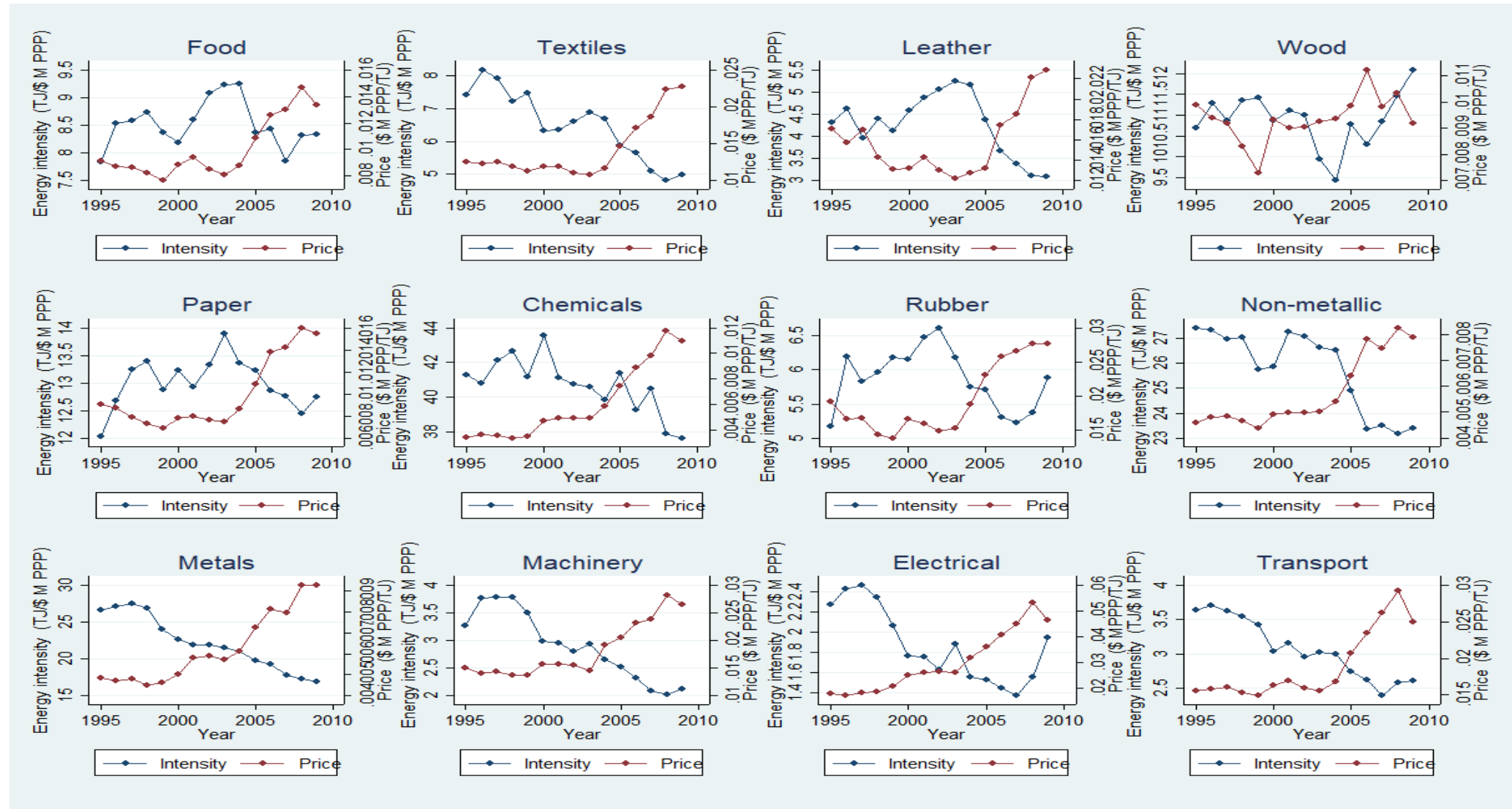
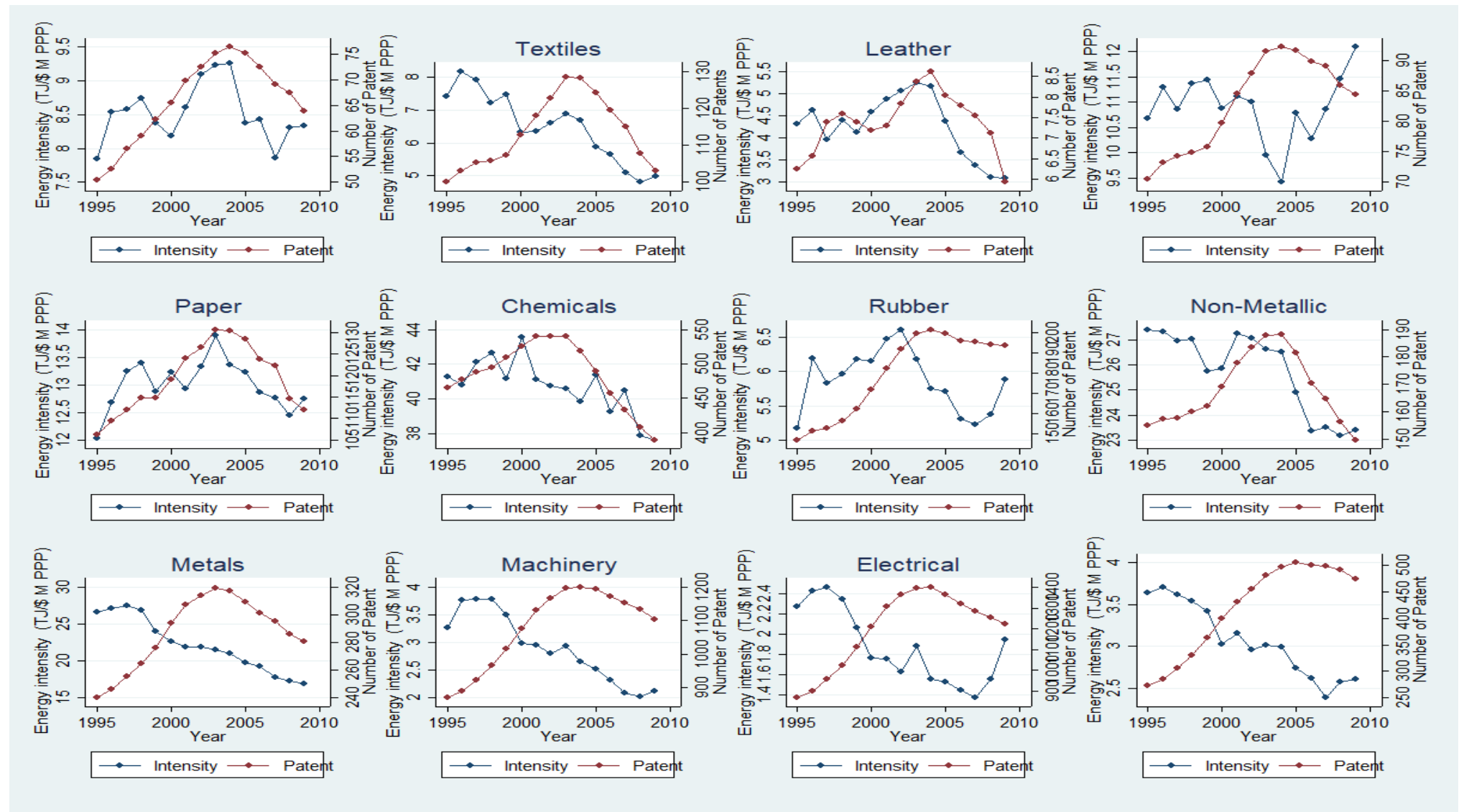
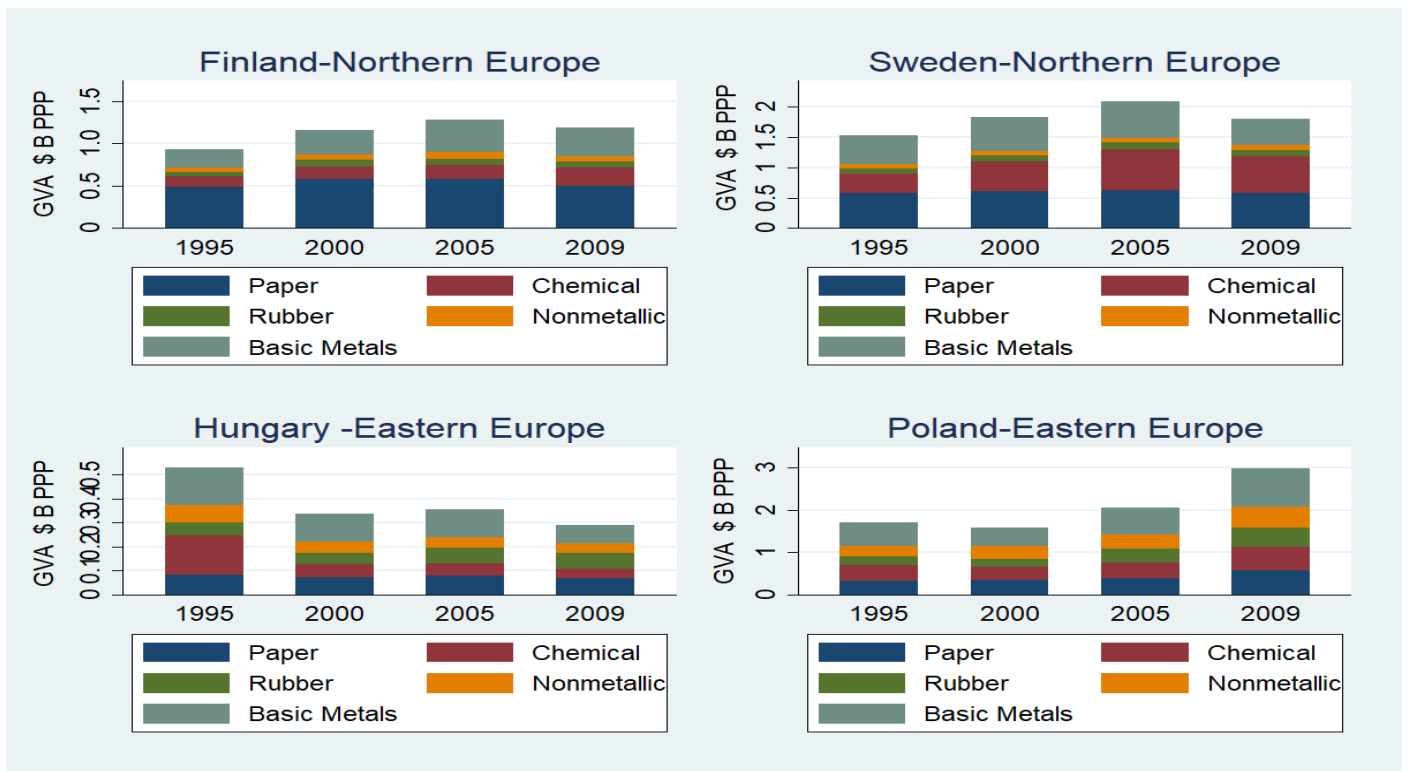


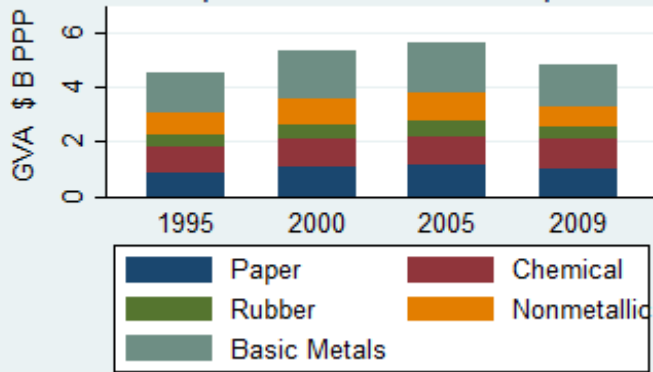
Figure A3: Time Series of Energy Intensity and Patent by Industry



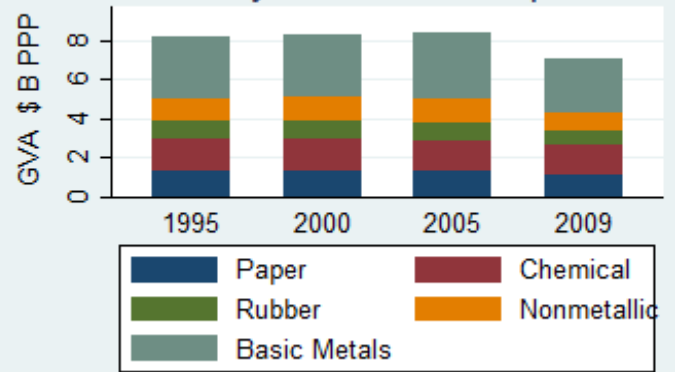
Appendix A10: Evolution of Gross Value Added of Energy Intensive Industries for selected countries



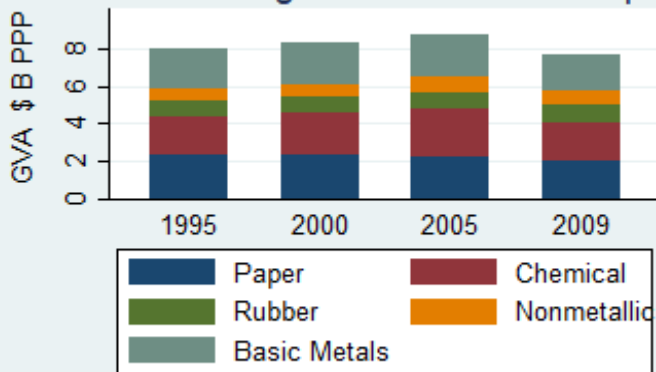
Spain - Southern Europe



Italy- Southern Europe



United Kingdom - Western Europe



Germany -Western Europe

