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The impact of Green Innovation on Energy Intensity

An Empirical Analysis for 14 Industrial Sectors in OECD Countries

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Résumé

Cet article analyse l'impact de l'innovation verte sur l'intensité énergétique dans un ensemble de 14 secteurs industriels pour 18 pays de l'OCDE sur la période 1975-2005. Notre méthodologie consiste à construire un stock de brevets verts pour chaque secteur industriel et à estimer une fonction coût translog pour mesurer l'impact de l'innovation verte - à côté d'autres déterminants tels que la substitution des facteurs de production et le progrès technologique autonome - sur l'intensité énergétique. Nos résultats montrent que l'innovation verte a contribué à la baisse de l'intensité énergétique dans la plupart des secteurs : l'élasticité médiane de l'intensité énergétique par rapport au stock de brevets verts est estimée à -0.03. Par conséquent, une augmentation de 1 % du stock de brevets verts dans un secteur donné est associée à une baisse de 0,03% de l'intensité énergétique dans le même secteur. Nos résultats montrent également que d'autres éléments, comme la substitution des facteurs de production et le progrès technologique autonome, jouent un rôle important dans le déclin de l'intensité énergétique par secteur.

Abstract

This paper analyzes the impact of green innovation on energy intensity in a set of 14 industrial sectors in 18 OECD countries over the 1975-2005 period. We create a stock of green patents for each industrial sector and estimates a translog cost function to measure the impact of green innovation, next to other factors such as input substitution and autonomous technical change, on energy intensity. We find that green innovation has contributed to the decline in energy intensity in the majority of sectors: the median elasticity of energy intensity with respect to green patenting is estimated at -0.03 in our sample. Hence, a 1% increase in green patenting activities in a given sector is associated with a 0.03% decline in energy intensity. Our results also show that other factors, such as input substitution and autonomous technical change, play an important role in explaining the decline in energy intensity per sector.

Abstrakt

Dieser Artikel analysiert den Einfluß grüner Innovation auf die Energieintensität in 14 Industriesektoren in 18 OECD-Ländern im Zeitraum zwischen 1975 und 2005. Unsere Methode besteht aus der Erstellung einer Datenbank von grünen Patenten für jeden Industriesektor und der Schätzung einer "translog" Kostenfunktion, um den Einfluß grüner Innovation auf die Energieintensität neben anderen Faktoren wie "input substitution and autonomous technical change" zu messen. Wir haben festgestellt, dass grüne Innovation zur Verringerung der Energieintensität in der Mehrheit der Sektoren beigetragen hat: die mittlere Elastizität der Energieeffizienz hinsichtlich grüner Patente in unserem Beispiel schätzen wir auf -0,03. Folglich entspricht die Erhöhung grüner Patente um 1% in einem Sektor einer 0,03-prozentigen Verringerung der Energieintensität. Unsere Ergebnisse zeigen zudem, dass andere Faktoren, wie beispielsweise "input substitution und autonomous technical change" eine wichtige Rolle bei der Verringerung der Energieintensität pro Sektor spielen.

Summary

Energy efficiency is at the core of the energy strategy in Switzerland, materialized in the *Energy Strategy 2050*. The strategy contains specific provisions to improve energy efficiency over a broad spectrum of activities, namely in construction, industry and services, mobility, electrical appliances and electricity supply.

Reducing the energy intensity of production processes is important to address climate change as it greatly contributes to reduce carbon emissions. According to recent estimates of the International Energy Agency, 31% of emissions reductions necessary to halve emissions by 2050 compared to 2009 levels can be achieved through this lever (IEA,2012). In addition, decreases in energy intensity contribute to the competitiveness of industries facing higher energy prices, which makes energy efficiency a `win-win' objective for policymakers and the private sector (Porter 1995). Finally, the decoupling of economic growth from energy use may also contribute to improve energy security.

Over the last decades, industrialized countries have witnessed a significant decrease in the energy intensity of their economies. According to recent studies, this decline is mainly explained by improvements within sectors, rather than across sectors. In other words, the decrease in energy intensity at the aggregate level is not explained by a composition effect, i.e. a shift to cleaner sectors in the economy, but rather the result of a more efficient use of energy within sectors of production. There are two main *within industry* sources of improvements, namely input substitution -- whenever firms substitute energy by using more labour or capital for instance, or technological innovation -- whenever firms save on energy by using new production techniques.

This paper analyzes the impact of green patenting activities on the energy intensity of 14 industrial sectors in 18 OECD countries over the 1975-2005 period. The objective is to clarify empirically the role of green technologies, such as heat exchange apparatuses or insulation, on the decline in energy intensity at the sector level. Earlier literature mainly focused on the role of energy prices on energy intensity, ignoring the role of technology. Our study is most related to Popp's (2001) work on the role of green patents on energy consumption. Compared to his work, which looked only at the US over the 1970-1990 period, we bring novel evidence for a much larger set of countries and a more recent time period.

Using the OECD Triadic Patent Families database, we identify green patenting activities using International Patent Classification (IPC) codes, as commonly used in the literature on green innovation. We allocate patents to countries by using the address of the inventor and then match patents to industrial sectors by applying a recently developed concordance table (Lybbert and Zolas, 2014) that relate IPC codes to their sectors of use (in NACE classification). For instance, according to this concordance table, green patents with the IPC code "Regeneration of Pulp liquors" have a probability of 85% to be used into the Pulp and Paper sector. We are thus able to construct stocks of green patents for each specific sector-country-year over the 1975-2005 pe-

riod. Data on energy intensity per sector are constructed using production data from the EU-KLEMS database (except for Switzerland for which we use data from the Swiss Federal Statistical Office). We also use data on other input (capital, labor, materials) quantities and volumes per industrial sector for the 1975-2005 period.

We estimate energy demand using a translog cost function in the line of the work by Berndt and Wood (1975). We decompose the technology variable between green patenting activities, non-green patenting activities, and autonomous technical change captured by a time trend. We estimate this equation using iterated three-stage least squares. We take advantage of the panel data structure to estimate the system of equations sector-by-sector while controlling for heterogeneity at the country level.

Our results show that an increase in green patenting activities is associated with a reduction in energy intensity in most of the sectors in our sample, with a median elasticity of -0.03. Hence, a 1% increase in green patenting activities in a given sector is associated with a 0.03% decline in energy intensity at the median. Interestingly, we find a statistically significant impact in all energy intensive industries, such as for instance “Manufacturing of coke, refined petroleum production”, “Chemicals”, “Rubber and plastics”, “Non-metallic minerals” and “Metals”. By contrast, sectors with a relatively low cost share of energy (e.g. “Textiles”) do not seem to benefit much from green patenting activities.
In additional robustness checks, we also include the stock of non-green patents per sector. We find that non-green patents do not decrease energy intensity as consistently as green patents. In terms of magnitude, the median impact of non-green patents is estimated at -0.01, roughly a third of the corresponding estimate for green innovation.

To gauge the overall contribution of green technology to the observed decline in energy intensity, we provide a decomposition exercise of the predicted long run change in energy intensity into various forces, in particular input substitution and the impact of technology. While predicted energy intensity decreased by 16% at the median between 1980 and 2005, we find that input substitution and technological change are found to contribute to a proportion of 50:50 to this decline. Within the estimated contribution of technology, 1/3 can be attributed to green patented innovation, 1/3 to non-green innovation, and 1/3 to autonomous technical change.

Next to our empirical estimates, we also provide descriptive evidence highlighting differences between Switzerland and the rest of our sample. As data for Switzerland are only available for 4 sectors over 6 years, we cannot conduct specific estimations for Switzerland. Overall, industrial sectors in Switzerland consume relatively less energy than the OECD average. The cost share of energy ranges between 0.3 and 2.5% in Switzerland, compared to 1 and 9% across the rest of our sample for the same subset of industries. Economic activities in Switzerland have also become relatively more energy-efficient over time. The average cost share of energy across the various sectors under study has declined between 2001 and 2004, whereas the average cost shares across OECD countries remained mostly flat. This highlights that

there are important structural differences between Switzerland and other OECD countries, as reflected by the input mix in each industry. In terms of green patenting activities, we find that Switzerland is ranked as the 6th largest innovator in green technologies over 1975-2005 in our sample.

Altogether, our descriptive analysis combined with our estimation results suggests that green innovation can greatly contribute to improve the energy-efficiency of production processes. Our results show that an increase in green patenting activities leads to a significant decrease in energy intensity. Although the impact (i.e. an elasticity of -0.03 at the median) may seem modest, its magnitude is larger in energy-intensive sectors and also larger than an average non-green patent. Hence, our results evaluating the impact of green technological change on energy-efficiency improvement are particularly useful to inform policymakers. In the context of Switzerland, our results underline that policy initiatives aiming to encourage green innovation such as the “Action plan for coordinated energy research” which sets innovative research and development as one of the main pillars of the new energy strategy will effectively contribute to improve the energy efficiency of production processes in Swiss industries.

Besides green innovation, our results also emphasize an equally important role for input substitution in explaining the observed decline in energy intensity per sector. This implies that rising energy prices lead firms to substitute energy for other inputs in their production processes. Hence, public policies putting a higher price on energy, such as current proposals in the *Energy Strategy 2050,* are also likely to yield important energy efficiency gains.

Contents

1 Introduction

Reducing the energy intensity[1] of production processes is a core objective of climate policies since it is an important mean to reduce carbon emissions. According to recent estimates of the International Energy Agency, 31% of emissions reductions necessary to halve emissions by 2050 compared to 2009 levels can be achieved through this lever (IEA, 2012). In addition, decreases in energy intensity contribute to the competitiveness of industries facing higher energy prices, which makes energy efficiency a 'win-win' objective for policymakers and the private sector (Porter and Van der Linde, 1995). Finally, the decoupling of economic growth from energy use may also contribute to improve energy security and the resilience of economies depending on energy imports.

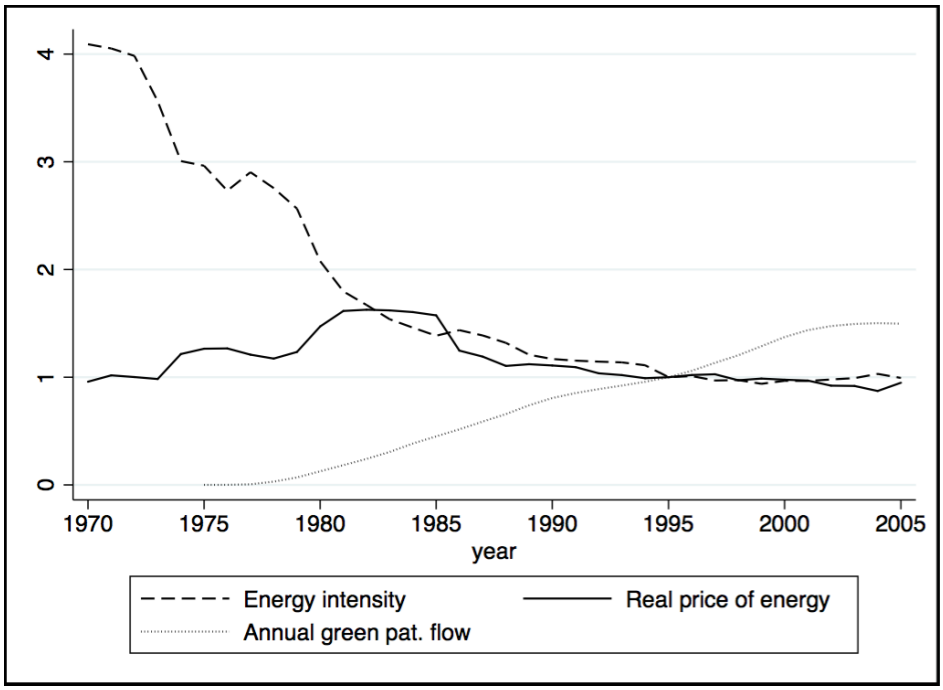
Over the last decades, industrialized countries have witnessed a significant decrease in the energy intensity of their economies. As shown in Figure 1, energy intensity, i.e. the quantity of energy used per unit of production value, declined by a factor of 5 over the 1970-2005 period. According to recent studies (e.g. Mulder and de Groot, 2012; Voigt et al., 2014), this decline is mainly explained by improvements within sectors, rather than across sectors. In other words, the decrease in energy intensity at the aggregate level is not explained by a composition effect, i.e. a shift to cleaner sectors in the economy, but rather the result of a more efficient use of energy within industries. There are two main *within industry* sources of improvements, namely input substitution – whenever firms substitute energy by using more labour or capital for instance, or technological innovation – whenever firms save on energy by using new energy-efficient production techniques. As an illustration, Figure 1 shows that the stock of green technologies, as proxied by the cumulative number of green patenting activities over time in our set of 18 OECD countries[2], has been steadily increasing over time since the 1980s. Since an increase in energy prices can trigger both a substitution of inputs away from energy and innovation in green technologies, Figure 1 also plots the evolution of the prices of energy over time. While energy intensity seem to be negatively correlated with energy prices until mid-1980s, the relationship is less clear for the second part of the sample period.

The objective of the current study is to clarify empirically the role of green technologies for

[1]Energy efficiency is defined as a technical measure, i.e. a ratio of input and output, whereas energy intensity refers to the quantity of energy used over the value of production.

[2]The precise definition of the stock of green patents is given in Section 3.

Figure 1: Energy Intensity, real prices of energy and green patent stocks: OECD average



Notes: All data have been normalized so that 1995 = 1 and are averaged across sectors. Energy intensity is the ratio of an index of quantity of energy to value of output. Green patent stock is the average of the sector-specific stock of energy efficient patents. Real prices of energy are indexes of constant 1995 USD.

the decline in energy intensity for a set of 14 industrial sectors in 18 OECD countries over the 1975-2005 period. Green technologies are defined as technologies impacting energy usage, such as insulation or heat exchange apparatuses. Using the OECD Triadic Patent Families database, we identify green patenting activities using International Patent Classification (IPC) codes (Johnstone et al., 2010; Popp, 2001) and match patents to industrial sectors by applying a recently developed concordance table (Lybbert and Zolas, 2014). This allows us to compute the stock of relevant green innovation for each industrial sector in our set of OECD countries. Using production data at the industry level from the EU-KLEMS database, we estimate a translog production function following the (widely-used) framework developed by Berndt and Wood (1975) (see for example Haller and Hyland, 2014; Kim and Heo, 2013; Arnberg and Bjorner, 2007) to measure the impact of green patents on energy intensity per sector. We find that an increase in green patenting activities is associated with a reduction in energy intensity in most of the sectors in our sample, with a median elasticity of -0.03. Hence, a 1% increase in green patenting activities in a given sector is

associated with a 0.03% decline in energy intensity at the median. Furthermore, we show through a decomposition exercise that half of the decrease in energy intensity is caused by changes in input prices and half is caused by changes in production technologies. Within the estimated contribution of technology, 1/3 can be attributed to green patented innovation, 1/3 to non-green innovation, and 1/3 to autonomous technical change.

Our study is related to an extensive literature which has used input demand functions to identify substitution patterns, in particular between energy and capital, since the 1970's (Binswanger, 1974; Berndt and Wood, 1975; Apostolakis, 1990). This literature has mainly focused on the role of energy prices on the demand for energy and capital inputs. Instead, the impact of technology has been neglected as the latter is often simply modelled as a time trend in the demand equations (for example in Jorgenson and Fraumeni, 1981; Welsch and Ochsen, 2005; Ma et al., 2008). This presents important drawbacks. First, it does not allow to cater to the induced innovation literature, which states that when energy prices are high, firms will tend to innovate in order to develop energy-saving technologies (Hicks, 1932; Ahmad, 1966; Jaffe and Palmer, 1997; Newell et al., 1999; Acemoglu, 2002; Popp, 2002). Second, the use of a time trend allows to observe only aggregate technical change without pinning down the specific effect of energy-saving technologies. The major reasons for this simplification in the energy input demand functions were first the absence of global datasets on innovation, and second the need for concordance tables to relate technologies to their potential sector of use to bridge the gap between patents and industrial sectors.

Some recent papers have circumvented the lack of specific measure of technology by using past energy prices as a proxy for biased technical change (Sue Wing, 2008; Mulder et al., 2014). Sue Wing (2008), for example, finds that within-sector gains in energy intensity in the U.S. occur through price-induced substitution of variable inputs, adjustments in quasi-fixed inputs, and, to a limited extent, through price-induced innovation. However, the use of past energy prices as a proxy for biased technical change requires the *ex-ante* assumption that energy prices are indeed an incentive to innovate. In contrast, Popp (2001) presents an unique study on the role of energy-efficient innovation on sectoral energy intensity where technology is measured using patent data. He uses a concordance table based on Canadian industries, the Yale Concordance Table, to match technologies to their potential sectors of use and finds an estimate of -0.06 for the short run elas-

ticity between green technology and energy intensity averaged across all sectors.[3] Overall, his results suggest that price-induced input substitution and induced innovation decreased energy consumption by a factor of two-thirds and one-third respectively. However, his study is limited to the U.S. and to the 1972-1991 period, which leaves out an important time period in terms of green innovation. By contrast to Popp (2001)'s analysis which was limited to the US, our study brings novel insights on the impact of green innovation on energy intensity for a large set of OECD countries. This helps to uncover whether the US results can be generalized more broadly. In addition, our analysis is original as it covers three decades of data up to 2005, while Popp (2001)'s study was limited to the beginning of the 1990s.

The remainder of this paper is structured as follows. Section 2 describes our empirical methodology. Section 3 provides a discussion of our data sources as well as some descriptive statistics. Section 4 presents the estimation results. Section 5 concludes. We present additional insights for the specific case of Switzerland in Section 6.

2 Theoretical Framework

There is a large body of literature estimating energy demand using a cost function approach following the pioneering work of Berndt and Wood (1975).[4] We consider an industry's production function:

$$Y = f(K, L, E, M, T) \tag{1}$$

where $f(\cdot)$ represents an industry's technology that produces output Y using the four input factors: capital K, labor L, materials M and energy E, and T the level of technology. We transform Equation (1) into a cost function by using the duality theorem between production and cost functions (Shephard, 1953):[5]

$$C = g(P_K, P_L, P_M, P_E, Y, T)$$

[3]For more information on the Yale Canada concordance table, please refer to Evenson et al. (1991)

[4]Recent studies include Welsch and Ochsen (2005); Arnberg and Bjorner (2007); Ma et al. (2008); Kim and Heo (2013); Haller and Hyland (2014).

[5]Under the duality theorem, if the production function is twice differentiable, then there is a corresponding cost function that is also twice differentiable.

where C is the minimum cost required to produce Y and P_i is the i-th input price. This allows to circumvent the issue of estimating production functions with endogenous choice of inputs (Binswanger, 1974). As the level of inputs is a choice variable for firms, estimating econometrically a production function potentially violates the assumption of strict exogeneity of regressors, as there could be numerous factors affecting simultaneously the output level and the choice of inputs. By using input prices in a cost function framework, this particular problem is most likely avoided, as prices can be considered exogenous provided that sectors are small. In addition, for the purpose of estimation, a flexible functional form imposing no a priori restrictions on the elasticities of substitution is preferred to estimate $g(\cdot)$. We thus employ a translog cost function, which makes no restrictive assumptions on the estimated substitution elasticities and on the optimal path of input factor adjustments induced by price changes (Christensen et al., 1973), expressed as: [6]

$$\begin{aligned} lnC &= \beta_0 + \sum_i \beta_i lnP_i + \beta_Y lnY + \beta_T lnT \\ &+ \frac{1}{2}\beta_{YY}(lnY)^2 + \frac{1}{2}\beta_{TT}(lnT)^2 + \frac{1}{2}\sum_i\sum_j \beta_{ij} lnP_i lnP_j \\ &+ \sum_i \beta_{iY} lnY lnP_i + \sum_i \beta_{iT} lnT lnP_i \end{aligned} \tag{2}$$

with $i, j = K, L, M, E$. Slutsky symmetry condition is imposed by setting $\beta_{ij} = \beta_{ji}$. Because of the collinearity problem, an estimation of the first derivatives of (2) is preferred to a direct estimation of the cost function. Cost minimization w.r.t. input prices implies the following:

$$\frac{\partial lnC}{\partial lnP_i} = \beta_i + \frac{1}{2}2\beta_{iK}lnP_K + \frac{1}{2}2\beta_{iL}lnP_L + \frac{1}{2}2\beta_{iE}lnP_E + \beta_{iY}lnY + \beta_{iT}lnT \tag{3}$$

Under Shephard's lemma, assuming cost minimization, the demand functions for input i are equal to the derivative of expenditures with respect to price (i.e the cost shares for each input). Equation (3) equals the energy cost share:

$$\frac{\partial lnC}{\partial lnP_i} = \frac{\partial C}{\partial P_i}\frac{P_i}{C} = Q_i\frac{P_i}{C} = \frac{P_i Q_i}{C} = s_i \tag{4}$$

where s_i is the cost share of the i-th input. Hence, the cost share for each input is defined as:

[6] See Thompson (2006) for a discussion of the specification of the translog cost function.

$$s_i = \beta_i + \sum_j \beta_{ij} lnP_j + \beta_{iY} lnY + \beta_{iT} lnT \tag{5}$$

The inclusion of β_{iY} measures potential scale effects in production, or whether the size of the sector changes the cost share of inputs (for example if an increase in the output of the sector shifts the production function towards, say, more capital). The coefficient β_{iT} measures shifts due to technical change. To ensure homogeneity of degree one in prices (a doubling of all prices results in a doubling of total costs), the following restrictions are imposed:

$$\sum_i \beta_i = 1 \quad \text{and} \quad \sum_i \beta_{ij} = \sum_i \beta_{iY} = \sum_i \beta_{iT} = 0$$

Since cost shares sum up to unity, the disturbance terms sum up to one, making the covariance matrix singular. The estimation procedure involves dropping one of the equations from the equation system and normalizing all input prices.[7] Since the objective of our paper is to measure the contribution of green technologies in particular, we decompose the technology variable between green technology (G) and autonomous technical change captured by a time trend t:[8,9]

$$s_i = \beta_i + \beta_{iL} ln\frac{P_L}{P_M} + \beta_{iE} ln\frac{P_E}{P_M} + \beta_{iK} ln\frac{P_{Kt}}{P_M} + \beta_{iY} lnY + \beta_{iG} lnG + \beta_{it} t + \varepsilon_i \tag{6}$$

for $i = K, L, E$ with cross-equation symmetry imposed. We estimate this equation using iterated three-stage least squares (Berndt, 1991) such that results are not sensitive to the choice of the omitted equation. We take advantage of our panel data structure to estimate the system of Equations (6) sector-by-sector while controlling for unobserved heterogeneity at the country level.

We provide two different measures of the impact of technology on energy intensity. We first measure the elasticity of energy intensity with respect to green technology. To obtain this elasticity,

[7] The choice of numeraire should not affect the estimated elasticities. Here, following Welsch and Ochsen (2005), we use material input as numeraire.

[8] Obviously, different empirical specifications are possible, each answering different research questions related to innovation. For instance, one could focus on overall technical change and thus use total patents, or on directed technical change and use the share of green patents. In this paper we are primarily interested in measuring the impact of green technologies, among other because green and non-green patent stocks are highly correlated, and because the share of green patents does not vary much through time.

[9] This framework measures the input bias of technological change (a potential shift in the isoquant structure or slope), and thereby ignore Hicks neutral technological change affecting all inputs simultaneously. Empirical studies testing for evidence of neutrality of technological change usually reject it (Hesse and Tarkka, 1986; Hunt, 1986).

the first step is to derive energy intensity from the cost share functions as defined in Equation (6). Using the zero profit condition stating that $TC = p_Y Y$ and substituting into the definition of s_E, we are able to recover energy intensity E/Y (Welsch and Ochsen, 2005). We simply multiply s_E by $\frac{P_Y}{P_E}$:

$$s_E = \frac{P_E E}{TC} = \frac{P_E E}{P_Y Y}; \quad \frac{E}{Y} = \frac{P_Y}{P_E} s_E \tag{7}$$

The elasticity of energy intensity w.r.t. green technology is:[10]

$$\epsilon_{EG} = \frac{\partial ln(E/Y)}{\partial lnG} = \frac{\hat{\beta}_{EG}}{\hat{s}_E} \tag{8}$$

with $\hat{\beta}_{EG}$ and $\hat{s}_E$ respectively the estimated coefficients on green technological change in the energy demand equation and the sector-specific mean predicted cost share of energy.

Our second measure on the impact of technology on energy intensity allows us to gauge the overall contribution of green technology on the observed decline in energy intensity. To do so, we provide a decomposition exercise of the predicted long run change in energy intensity into various forces, namely input substitution, economies of scale, budget effect and the impact of technology (Welsch and Ochsen, 2005):[11]

$$\begin{aligned}
\hat{e} = \frac{P_Y}{P_E}\hat{s}_E &= \frac{P_Y}{P_E}\left[\hat{\beta}_E + \hat{\beta}_{EL} ln\frac{P_L}{P_M} + \hat{\beta}_{EE} ln\frac{P_E}{P_M} + \hat{\beta}_{EK} ln\frac{P_K}{P_M} + \hat{\beta}_{ET} lnT + \hat{\beta}_{Et} t\right] \\
&= \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_E\right]}_{\hat{e}_0} + \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_{EL} ln\frac{P_L}{P_M}\right]}_{\hat{e}_1} + \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_{EE} ln\frac{P_E}{P_M}\right]}_{\hat{e}_2} + \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_{EK} ln\frac{P_K}{P_M}\right]}_{\hat{e}_3} \\
&+ \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_{EG} lnG\right]}_{\hat{e}_4} + \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_{ENG} lnNG\right]}_{\hat{e}_5} + \underbrace{\left[\frac{P_Y}{P_E}\hat{\beta}_{Et} t\right]}_{\hat{e}_6}
\end{aligned}$$

We denote the terms on the right hand side of the equation as $\hat{e}_0, \hat{e}_1, ..., \hat{e}_6$. Each term represents

[10] Derivation can be found in A.

[11] In contrast with many applications of decomposition exercises in the literature, we perform sectoral decomposition rather economy-wide, which would require methods such as the mean Divisia Index (Ang and Liu, 2001; Fisher-Vanden et al., 2004; Voigt et al., 2014).

a specific effect on the change in predicted energy intensity over a given period. The constant term, $\hat{e}_0$ represents the budget effect, reflecting how price changes – P_Y and P_E – contribute to energy intensity at a given cost share (Welsch and Ochsen, 2005). In other words, this term captures how changes in the price of energy affect the quantity of energy which can be afforded at a given energy budget share. Next, the terms $\hat{e}_1$ to $\hat{e}_3$ measure the substitution between inputs, $\hat{e}_4$ measures the effect of green innovation, $\hat{e}_5$ measures the effect of non-green innovation, defined as the total stock of patents minus the stock of green patents, and $\hat{e}_6$ captures the effect of the time trend, measuring the effect of autonomous technical change.

We then allocate the observed long time change in energy intensity to each driving force as follows:

$$\frac{\Delta\hat{e}}{\hat{e}} = \sum_{i=0}^{6} \frac{\Delta\hat{e}_k}{\hat{e}_k}\frac{\hat{e}_k}{\hat{e}} \tag{9}$$

Where $\Delta\hat{e}/\hat{e}$ denotes the relative change in overall energy intensity in a specific sector over the time horizon and $\Delta\hat{e_k}/e_k$ denotes the relative changes over the time horizon of one specific effect $(\hat{e}_0, \hat{e}_1, ..., \hat{e}_6)$ with $\hat{e}_k/\hat{e}$ referring to the share of each effect in predicted energy intensity in the base year.[12]

3 Data and Descriptive Statistics

3.1 Patent data

Technological innovation is measured using patent counts. Besides being readily available, patents present the advantage of being a good indicator of innovative activity and tend to be highly correlated with a large number of alternative measures of innovation (see Acs and Audretsch, 1989; Comanor and Scherer, 1969; Griliches, 1990; Hagedoorn and Cloodt, 2003; Popp, 2005). We extract patent data for 18 countries from the OECD Triadic Patent Families (TPF) database (Dernis and Khan, 2004), over the 1975-2005 period.[13] Triadic patents families are patents

[12]To make the estimate less sensitive to the choice of initial base year, in Section 4 we take three year averages (1980-1982 and 2003-2005) to calculate changes in energy intensity.

[13]We consider the following countries: Austria, Belgium, Switzerland, Germany, Denmark, Spain, Finland, France, Great Britain, Italy, Japan, South Korea, Luxembourg, the Netherlands, Portugal, Sweden, Slovenia and the United States.

filed at the European, Japanese and US patent offices (respectively, EPO, JPO and USPTO) to protect the same invention.[14] These technologies tend to be of much higher economic value than patents filed only at a single national authority, as firms would only be willing to bear the substantial costs involved with filing a patent at the EPO, JPO and USPTO, if they expect their invention to be of high commercial value (Nesta et al., 2014). This quality hurdle thus removes low-value inventions, reducing the variance in patent quality (Johnstone et al., 2010), identified as one of the main challenges of methodologies using simple patent counts (Griliches, 1990; Popp, 2001). The use of triadic patents also has the advantage to reduce the home bias (Griliches, 1990): applicants tend to apply for patent protection in their home country more than in other countries, overestimating the stock of patent of domestic applicants compared to foreign applicants when relying on data from a single patent office.

Following Jaffe et al. (1993) (see also the OECD patent manual, 2009), we allocate patents to countries using the address of the inventor. When a patent is invented by multiple inventors located in different countries, we disaggregate them using fractional counts. We count patents per priority year, which is the date closest to the date of invention (see OECD, 2009, chapter 4).

3.1.1 Identification of green patents by sector

Our identification of the relevant green technologies uses the following strategy. In a first step, we start from the broadest possible list of green patented technologies – identified using International Patent Classification (IPC) codes. We use the extensive list of climate change mitigation technologies provided in Dechezlepretre et al. (2011) and expand it with the list of technologies more specifically relevant to energy-efficiency selected by Popp (2001). This gives us a list of 1,529 technology classes defined at the 6-digit IPC code.[15] We use fractional counts for patents with several IPC codes. If a given patent specifies two technological fields, among them only one relevant for our analysis, 0.5 patent will be allocated to the prevailing country/year.

In a second step, we relate patents (coded in IPC) to their sectors of use (coded in ISIC or NACE), i.e. sectors in which these specific technologies are used in the production process. We rely on the recently released ALP ('Algorithmic Links with Probabilities') concordance table de-

[14] For a typology of patent families, please refer to Dernis and Khan (2004) or Martinez (2010).

[15] Table A1 in Appendix A.3 exhibits a selection of the corresponding technology classes (aggregated at the 4-digit IPC level for brevity). The complete list of IPC codes can be provided upon request.

veloped by Lybbert and Zolas (2014) together with the World Intellectual Property Organization (WIPO). This table makes it possible to link patents and economic data through technology-industry associations. The authors use a text analysis software and keyword extraction programs to develop a probability distribution of possible industries with which a patent in a given technology field may be associated. For each patent, the table provides us with a list of economic sectors with a corresponding probability.[16] In essence, these probability weights blend two types of links, namely *usage* and *production* of technologies (Lybbert and Zolas, 2014), reflecting the fact that technologies are allocated to industries either because they are used therein, or because the technology was developed by this industry. Yet, in their robustness analysis, Lybbert and Zolas (2014) find that there are only negligible differences between their estimated weights and the weights of other methodologies distinguishing between sector of use and industry of manufacture (Lybbert and Zolas, 2014, p. 537). While the concordance table allows us to screen out green patents that are not being used in a given sector (e.g. solar technologies in the pulp-and-paper industry), we may be concerned about two remaining sources of measurement errors.

First, some patents identified as green could still be unrelated to energy consumption. For instance, end-of-pipe technologies, such as a pollution filter, may be selected as green patents but are not likely to affect energy usage. This could result in an overestimation of the stock of patents compared to energy-efficient patents narrowly defined, thereby adding statistical noise and blurring our estimations. To check the relevance of this concern, we identified the 'sectors of use' as provided by the concordance matrix for renewable energy patents (wind, solar, hydro, marine and biomass) for which the energy-saving characteristics are the least obvious. Most of these technologies are allocated to the sector NACE 40 (Generation of electricity), as expected, but also fall in other industrial sectors with a small probability. As an illustration, wind technologies are allocated with a 0.72 probability to electricity production, but also with a probability of 0.125 to NACE 29 (Machinery nec).

As a result, we choose to keep these patents in our sample selection. An overestimation of

[16]Several modifications are made. First, because the concordance table developed by Lybbert and Zolas (2014) provide the sectors of use in ISIC 3.1 code, while our production data is provided in NACE rev.1.1, we use the concordance table from the United Nations Statistical Division to match sector codes (available at http://unstats.un.org/unsd/cr/registry). Second, the output from the concordance table is provided in disaggregated NACE sectors (1.11, 1.12, 1.13), while EU-KLEMS data is provided only in aggregated NACE (11). We thus simply add up the weights provided by the table for each of the aggregated NACE codes.

the stock of patents could increase the risk finding no statistically significant coefficient when the true parameter value in fact is significant. This does not, however, prevent us to make conclusive arguments on parameters found significant as long as these are uncorrelated with the error term.

An additional measurement error can arise as, although we use the most comprehensive list of green IPC codes available, in theory there might exist additional energy-efficient technologies excluded from our selection. In this case, we might be underestimating the stock of green knowledge, implying that our estimates may be only a lower bound. Again, this does not prevent us from making conclusive arguments on parameters found significant.

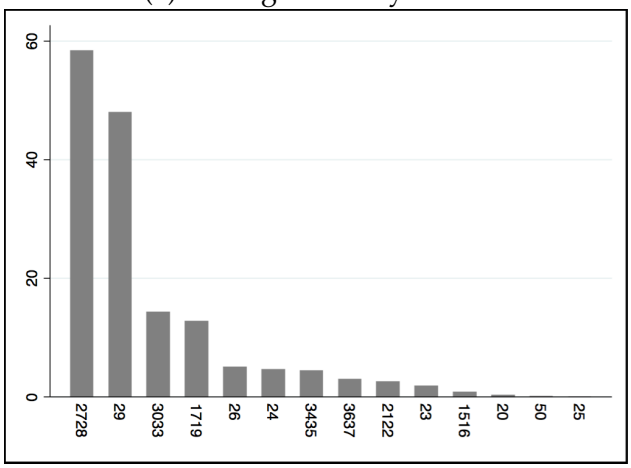
Table 1 summarizes the list of IPC classifications related to each sector and the associated concordance weight from Lybbert and Zolas (2014), for a selection of industries: NACE sectors 21 (Pulp and Paper), 24 (Chemicals), 27 (Basic metals) and 28 (Fabricated Metals). For example, the probability weight between the green IPC class D21C11 (Regeneration of pulp liquors) and the NACE sector 21t22 (Pulp & Paper) is 85%. In words, this technology has a probability of 85% of being used in this sector. We then count the number of patents allocated to each sector of use weighted by the corresponding probabilities. For example, if there are 10 patents in this IPC classification in a given year (each with only a single inventor and a single IPC code), a flow of 8.5 patents will be allocated to this industrial sector. Note that weights for each technology class sum up to one, such that the total count of patents remains unchanged after being split between sectors of use.

Table 1: Sectors and technologies (selection)

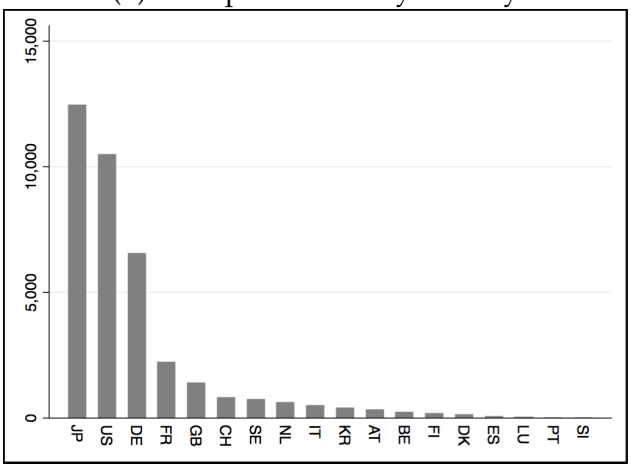
NACE rev. 1.1	Sector name	IPC	Category	Conc. weight
21	Pulp and Paper	D21C11	Regeneration of pulp liquors	0.8463
24	Chemicals	C25D13	Processes for the Electrolytic Production of Coatings	0.3767
24	Chemicals	C23C16	Coating Metallic Material	0.1990
24	Chemicals	C23C22	Coating Metallic Material	0.1325
24	Chemicals	C12M1	Methane capture	0.1235
24	Chemicals	C02F11	Methane capture	0.1200
24	Chemicals	H01L25	Semiconductor devices	0.0897
24	Chemicals	C02F11	Methane capture	0.0782
24	Chemicals	D21C11	Regeneration of pulp liquors	0.0721
24	Chemicals	C25D9	Processes for the Production of Coatings	0.0698
24	Chemicals	C10L1	Waste	0.0641
27	Basic Metals	C25C3	Coating Metallic Material	0.9315
27	Basic Metals	C25C1	Refining of Metals	0.8373
27	Basic Metals	C21D8	Methods or devices for heat treatment	0.8167
27	Basic Metals	B22D21	Casting of Metals	0.7585
27	Basic Metals	C21D6	Methods or devices for heat treatment	0.7380
27	Basic Metals	C25C5	Coating Metallic Material	0.7030
27	Basic Metals	C25D11	Processes for the Production of Coatings	0.6741
28	Fabr. Metals	C25D2	Processes for the Production of Coatings	0.7524
28	Fabr. Metals	C23C30	Coating Metallic Material	0.6722
28	Fabr. Metals	C23C18	Coating Metallic Material	0.6122
28	Fabr. Metals	C25D7	Processes for the Production of Coatings	0.6085
28	Fabr. Metals	C23C28	Coating Metallic Material	0.5876

Figure 2: Average green patent stocks

(a) Average stock by sector



(b) Total patent flow by country

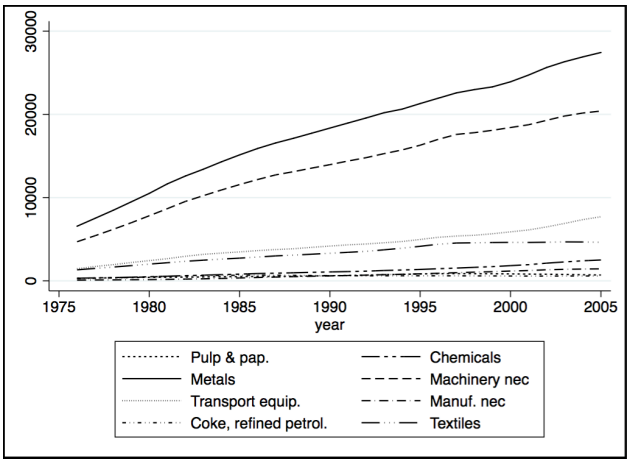


3.1.2 Descriptive statistics of patent stocks

We compute cumulative green patent stocks over the 1970–2005 period for our set of 18 OECD countries using the perpetual inventory method with a 10% yearly depreciation rate (Verdolini and Galeotti, 2011) to the counts of patents per sector/country/year. Figure 2a shows the average patent stock allocated to each sector across countries.[17] Sectors with the largest stocks of green patenting activities are sector 27t28 (Metals), 29 (Machinery nec), 30t33 (Office and accounting; electrical engineering; medical, precision and optical instr.) and 17t19 (Textiles, textile products, leather and footwear). In contrast, some sectors have a very low number of green patents throughout the sample, namely: 15t16 (Food, beverages and tobacco), 25 (Rubber and plastics) and 50 (Sale, maint. and repair of motor vehicles; retail sale of fuel). Figure 2b gives the total number of green patents per country (aggregated over all sectors). Green innovation appears to be highly concentrated geographically: most innovation is performed by inventors in Japan, but also in the United States, Germany and South Korea, as commonly found in the literature. Finally, Figure 3 shows the evolution of the stock of green patents over time (averaged across all 18 OECD countries in our sample) for a selection of industrial sectors. Patent stocks broken down by industry increase steadily through time in most cases.

[17] Effective green patents are green patents weighted by the inventor fractional counts, and allocated to sectors by the concordance table.

Figure 3: Green patent stocks (OECD average)



3.2 Input demand functions

We use production data at the industry level from the EU-KLEMS database, March 2008 version (with the exception of Switzerland).[18] This dataset is developed from supply-and-use tables to recover energy, materials and services from total intermediate inputs as provided by National Accounts, and is widely used to estimate input demand functions (see for example Mulder and de Groot, 2012; Kim and Heo, 2013; Steinbuks and Neuhoff, 2014).[19] Data on input quantities and volumes per industrial sector over the 1970-2005 period are available for the following inputs: energy, material, labor and capital. Sectoral implicit prices of inputs are recalculated from input expenses (CAP, LAB, IIE and IIM) and volume indexes (CAP_QI, LAB_QI, IIE_QI and IIM_QI) available in the the 2008 version of EU-KLEMS. We normalize expenses and divide them by volume indexes ($1995 = 100$) to obtain current energy purchaser's price indexes. Table 2 lists the industries included in our sample.[20]

Switzerland is included in all the estimations provided in this paper. To include Switzerland, we borrow data from Mohler and Mueller (2011), who assembled a dataset used to measure production elasticities. Due to limitations in coverage, data for each of our relevant variables is available for 6 years only (1999-2005) for 4 sectors: 17t19 (Textiles and textile products), 2122 (Pulp and

[18] Available at www.euklems.net.

[19] O'Mahony and Timmer (2009) provide a complete description of the methodologies used to build the EU-KLEMS dataset.

[20] Some sectors are aggregated to maximize sample size, while others are removed due to missing observation.

Table 2: Sectors

NACE rev. 1.1	sector name
15t16	Food, beverages and tobacco
17t19	Textiles, textile products, leather and footwear
20	Wood and products of wood and cork
21t22	Pulp, paper and paper products, printing and publishing
23	Manufacture of coke, refined petroleum products and nuclear fuel
24	Chemicals
25	Rubber and plastics
26	Non-metallic minerals
27t28	Metals
29	Machinery nec
30t33	Office and accounting; electrical engineering; medical, precision and optical instr.
34t35	Transport equipment
36t37	Manufacturing nec; recycling
50	Sale, maint. and repair of motor vehicles; retail sale of fuel

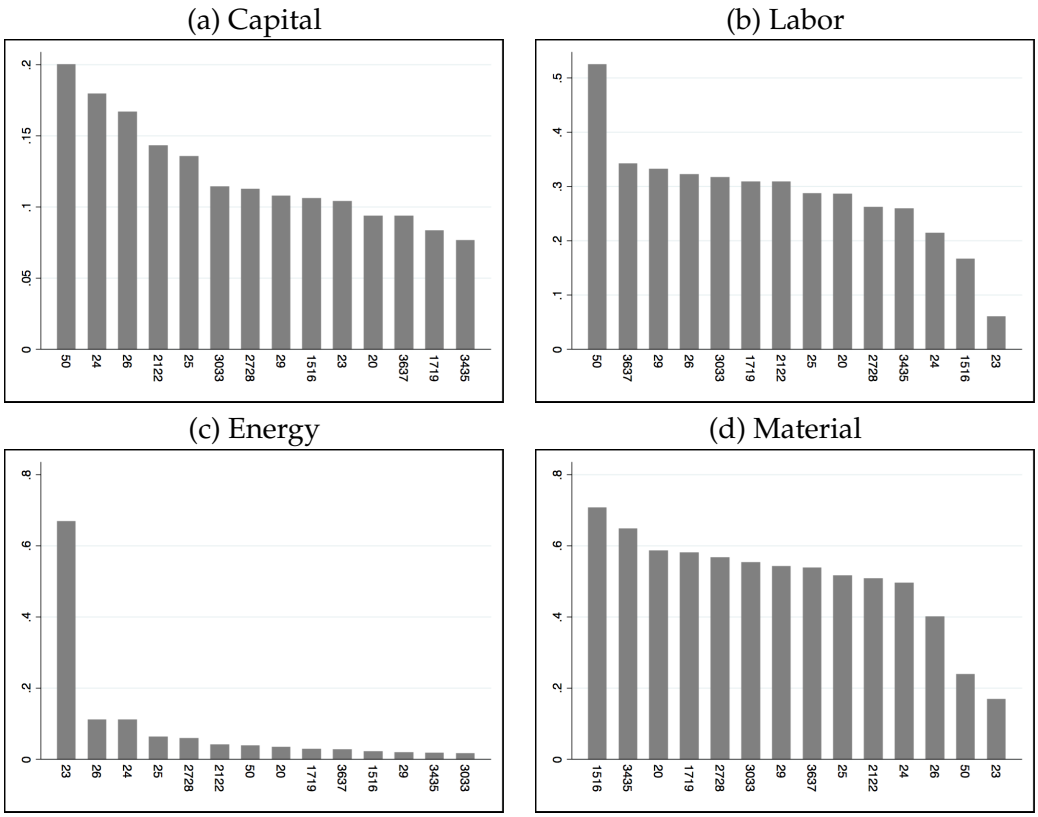
paper), 26 (Non-metallic minerals) and 29 (Machinery nec).[21]

Figure 4 presents the share of each input (capital, labor, materials, energy) in total costs, our main dependent variable. Figure 8 plots the evolution of the cost share attributable to energy input over time for various industries. The cost share of energy tends to decrease through time and this decline is particularly strong over the first sample period (1980-1995).[22] Figure 4 shows that sector 23 (Manufacture of coke, refined petroleum products and nuclear fuel), which is measured on the

[21]Sectors 15t16 (Food, beverages and tobacco) and 24 (Chemicals) are presented in the descriptive stats section but are absent from the econometric estimation due to lack of data on physical input quantities used. Data for output, material and labor expenditures come from the Swiss Federal Statistical Office (SFSO) in the Produktions- und Wertschopfungsstatistik. Energy expenditures are calculated by using the survey EVID from the Swiss Federal Office of Energy (SFOE) which includes the physical quantities of different energy sources used by manufacturing sectors. We then calculate the energy expenditures of each sector by using energy prices published by the IEA and the SFOE and the physical quantities from the EVID database. Capital expenditures are calculated as a residual by taking the difference of sales, material, labor and energy expenditures. For the price indices used in the analysis, we employ output and material price indices available from the OECD. We use a wage index from the survey Sammelstelle fur die Statistik der Unfallversicherung published by the SFSO. Sectoral energy price indices are calculated by using a weighted average of price indexes for each energy source based on physical quantities. Capital price indices are not available for different manufacturing sectors in Switzerland. We use an investment/capital goods import price index published by the Swiss Federal Customs Administration (EZV) to proxy capital price changes as we are mainly interested in the price evolution of physical capital.

[22]One needs to bear in mind that being a share, this variable can also be affected by movements in the consumption of other inputs. An increase in the use of, say, labor, will mechanically affect the cost share of other inputs. A simple graphical analysis is thus limited in this respect.

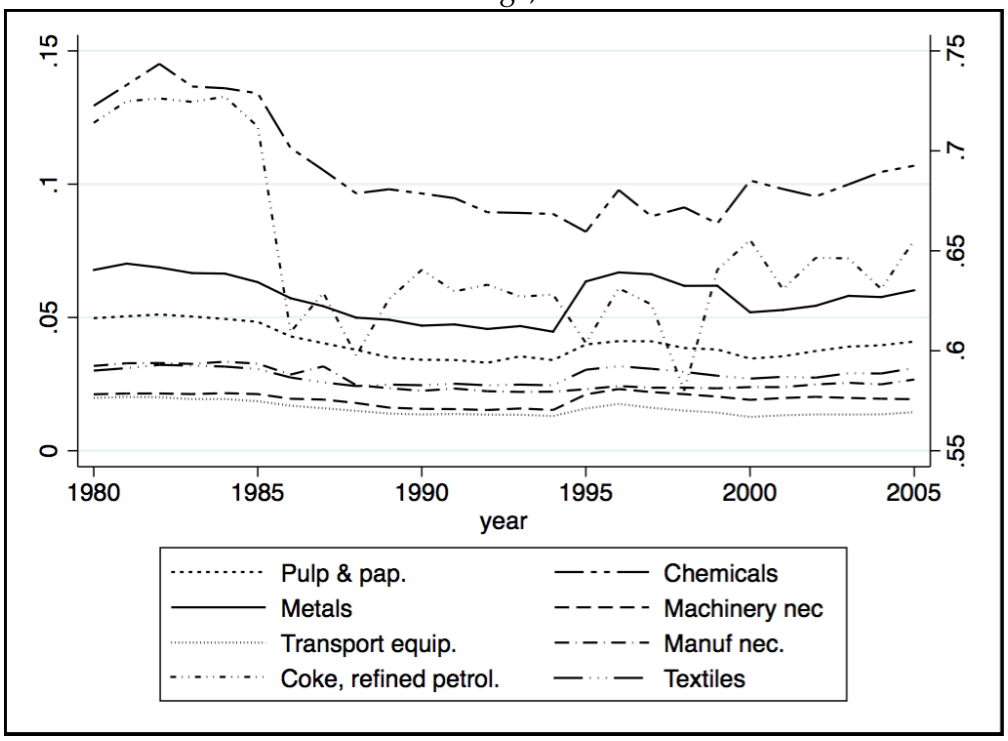
Figure 4: Cost shares by sector: OECD, all sectors



right-hand scale is by far the most intensive in energy as a proportion of total input costs, followed by sectors 26 (Non-metallic minerals), 24 (Chemicals), 25 (Rubber and plastics) and 27t28 (Metals). Summary statistics of our dataset are presented in Table B1 in B.

Figure 5: Cost share of energy

OECD average, 1980-2005



Note: Right-scale used for Sector 23, Coke and refined petrol. (dash-dotted line)

4 Results

In this section, we present our main results. We estimate the system of equations (6) from Section 2 sector-by-sector, and recover parameters and corresponding elasticities with respect to technology as defined in Equation (8). We use a one-period lag for knowledge stocks to account for potential reverse causality between green innovation and energy intensity (changes in energy demand can affect the incentive to innovate), which simultaneously allows for a time lag between disclosure of patented innovation and effective implementation in industrial sectors. Table 3 shows the estimates of the technology coefficients for the cost share of energy (β_{EG} and β_{Et}), the corresponding own-price elasticity ($\eta_{E,PE}$), and the elasticity of energy intensity with respect to green knowledge stocks ($\epsilon_{E,G}$).[23,24] For a given sector, our sample includes 18 countries over

[23]Complete parameter estimates for other factor shares, sector by sector, are not included for sake of brevity, and will be provided upon request.

[24]For price variables, elasticities are reported because coefficients as such provide little interpretation (Binswanger, 1974): the coefficient on the price of energy for the cost share of energy ($P_e * E$), for example, mixes a direct effect (the

31 years, although some observations can be missing. Because previous literature highlighted important differences across countries (Voigt et al., 2014), all our equations include country fixed effects to account for country-specific unobserved heterogeneity.[25]

As can be seen in Table 3, the coefficients on green knowledge stocks (β_{EG}) are negative in 8 out of 14 sectors. These results are somewhat consistent with the findings of Popp (2001), where a negative elasticity of energy w.r.t. energy-efficient technology is observed for 8 out of 13 industrial sectors, though precise cross-study comparison is limited due to differences in the definition of sectors and aggregation levels. In terms of magnitude, our median estimate for the elasticity of green knowledge stocks ($\epsilon_{E,G}$) is -0.033. In other words, a 1% increase of a sectoral green knowledge stock decreases the energy intensity by approx. 0.03% in the next period, with a maximum value of 2.07% found for sector 25 (Rubber and plastics).

Interestingly, industries with the highest average cost share of energy, i.e. with the highest potential economic gains from energy productivity improvements – 23 (Man. of coke, refined petroleum prod. and nuclear fuel), 24 (Chemicals), 25 (Rubber and plastics), 26 (Non-metallic minerals) and 27t28 (Metals) – all present negative and significant impact of green innovation.[26] This result is reassuring, and could be interesting from a policymaking perspective. Energy consumption could be reduced through innovation in industries where it is largest, which would thus translate in large gains at the aggregate level.

In contrast, some sectors seem less sensitive to green innovation, despite a large number of patents throughout our sample, as shown previously in Figure 2, namely sectors 17t19 (Textiles, textile products, Leather), 29 (Machinery nec), 30t33 (Office, account.; electric., medic. and precis. engin.) and 34t35 (Transport equipment). This could again be related to the potential gains from energy-saving innovation. Indeed, the cost share of energy in all of these sectors is lower than 2%.[27]

initial increase in price increases the factor share) and a substitution effect (the subsequent decrease in quantity lowers the factor share), having thus an ambiguous effect.

[25] An important aspect to consider is that although excluding control variables for energy subsidies, energy export restrictions, or any exogenous shocks on energy demand, our econometric framework implicitly controls for factors impacting input prices.

[26] The average cost share of energy for these sectors amounts respectively 67%, 11%, 6%, 10% and 5%, whereas the average for the rest of the sample is 2.6%.

[27] The positive and significant impact in NACE 29 could be caused by the vague definition of industrial activities. As this sector is defined as a residual of machinery and equipment technologies not elsewhere classified, we expect it to cover a large number of very heterogenous activities. This could affect both the dynamic of energy intensity, as well as its corresponding allocation of patents.

The coefficient associated with the time trend variable (β_{Et}) is negative and statistically significant in 8 out of 14 industries. This result suggests that autonomous technical change also plays an important role for the decrease in energy usage in some industries.

Table 3 also presents the estimates of own-price elasticities for energy ($\eta_{E,PE}$). The negative elasticities of energy consumption w.r.t. the price of energy suggest that price induced input substitution also affects energy consumption in most sectors. Furthermore, these estimated values of the own-price elasticities provide us with a way to verify the properties of our cost functions.[28] In Table 3, one can see that the own-price elasticity of energy is negative for all sectors, confirming that energy usage responds negatively to price changes, as expected. The magnitude of the estimated elasticities is -0.528 for the median value. A 1% increase in the price of energy decreases energy demand by 0.528% at the median, close to the range of estimates previously found in the literature.[29]

As robustness check, we include the stock of patents not identified as green, calculated by subtracting the stock of green patents from the total stock of patents. This affords an indirect mean to control for the robustness of our identification of patents expected to affect energy intensity, as well as to account for potential cyclical trends in the number of general patent applications. Estimates are presented in Table 4. Although multicollinearity could reduce the statistical significance of some estimates, this does not prevent us to make conclusive arguments on parameters that are found significant.[30] We observe that non-green patents do not decrease energy intensity as consistently as green patents. In terms of magnitude, the median impact of non-green patents is estimated at -0.01, roughly a third of the corresponding estimate for green innovation. Furthermore, the estimates for green patents remain close to our baseline specification with a median elasticity of energy intensity w.r.t. green patents of -0.033, compared to -0.038 estimated previously.

Table 5 shows the results of our decomposition exercise as specified in Equation (9) between 1980 and 2005 based on estimates in Table 4.[31] This affords a way to gauge the impact of each

[28] A cost function concave in input price reflects non-zero input substitution. This property of concavity of input demand is not necessarily verified in the case of the translog functional form. Derivation of input price elasticities are also provided in A.

[29] See for example Berndt and Wood (1975), or Popp (2001), who finds an average of -0.680.

[30] The correlation between the log of the stock of green and non-green patents, as included in our regressions, equals 0.8.

[31] Only countries/sectors with a non-zero patent stock throughout the sample are included. The selected time period is 1980–2005 to limit the number of missing observations.

factor on the long term change in energy intensity: the long term change in predicted energy intensity is decomposed between the budget effect, input substitution (capital, labor and energy), economies of scale (output) and the technology effect (green patent stocks and time trend). At the median, predicted energy intensity decreased by 16% between 1980 and 2005.

Input substitution ($\hat{e}_1 - \hat{e}_3$) and technological change ($\hat{e}_4 - \hat{e}_6$) are found to contribute to a proportion of 53:47 to the decrease in long term predicted energy intensity. In other words, in the long term, both factors seem to affect energy intensity in the same proportion: roughly half of the decrease in energy intensity is caused by changes in input prices and half is caused by changes in production technologies. Furthermore, within the estimated contribution of technology, 35% can be attributed to green patented innovation, 30% to non-green innovation, and 35% to autonomous technical change. The equal contribution of input substitution and technological change on the decline in energy intensity provides two important insights for policymakers. First, the fact that an increase in energy prices induce a substitution away from energy towards other relatively cheaper inputs implies that public policies putting a price on carbon are likely to be effective in reducing the energy intensity of production processes. Second, as innovation in green technologies is also effective in reducing the energy intensity of industries, there is a role for policies encouraging green innovation in particular, for instance in the form of government energy R&D investment.

Table 3: Baseline results

Sector	N	β_{EG}	β_{Et}	$\eta^{\mathbf{a}}_{E,PE}$	$\epsilon^{\mathbf{b}}_{E,G}$
Food, beverages and tobacco	405	-0.0016***	0.0002***	-0.765	-0.066
		(0.0005)	(0.0001)		
Textiles, textile products, Leather	395	-0.0001	0.0006***	-0.370	-0.003
		(0.0005)	(0.0001)		
Wood and products of wood and cork	393	-0.0095***	0.0010***	-0.656	-0.267
		(0.0027)	(0.0002)		
Pulp, paper and paper prod., print. and publish.	412	-0.0024***	-0.0004***	-0.508	-0.054
		(0.0009)	(0.0001)		
Man. of coke, refined petr. prod. and nucl. fuel	353	-0.0299***	-0.0001	-0.209	-0.044
		(0.0054)	(0.0005)		
Chemicals	405	-0.0064***	-0.0010***	-0.548	-0.056
		(0.0023)	(0.0004)		
Rubber and plastics	403	-0.1394***	0.0008***	-0.472	-2.066
		(0.0402)	(0.0002)		
Non-metallic minerals	412	-0.0029*	-0.0004*	-0.448	-0.027
		(0.0016)	(0.0002)		
Metals	405	-0.0023***	-0.0003**	-0.418	-0.040
		(0.0006)	(0.0001)		
Machinery nec	412	0.0006**	-0.0003***	-0.642	0.033
		(0.0003)	(0.0001)		
Office, account.; electric., medic. and precis. engin.	399	0.0000	-0.0001**	-0.610	-0.001
		(0.0003)	(0.0001)		
Transport Equipment	392	0.0002	-0.0004***	-0.845	0.011
		(0.0004)	(0.0001)		
Manufacturing nec; recycling	400	-0.0007	0.0007***	-0.625	-0.027
		(0.0008)	(0.0001)		
Sale, maint. of motor vehic.; retail sale of fuel	388	0.0078	0.0007***	-0.440	0.215
		(0.0197)	(0.0001)		
Median		-0.0020	-0.0001	-0.528	-0.033
Coeff. < 0		10	8		
Coeff. > 0		4	6		

Notes: [a]Own-price elasticity of energy as defined by Equation (A4). [b]Short run elasticity of energy intensity w.r.t. green knowledge stock as defined by Equation (8). All elasticities calculated using mean levels of cost shares by sector: $s_{Ei} = \frac{1}{N}\sum_{i=1}^{n}\frac{P_{E,in}Q_{E,in}}{TCin}$ for sector i, averaged over countries 1...N. All estimations are by sector, based on the spec. with domestic, green stocks of granted patents, with country FE. Standard errors in parentheses. p***$\leq$ 0.01, p**$\leq$0.05, p*$\leq$0.1.

Table 4: Green vs. non-green patents

Sector	N	β_{EG}	β_{ENG}	β_{Et}	$\epsilon^{\mathbf{a}}_{E,G}$	$\epsilon^{\mathbf{b}}_{E,NG}$
Food, bev. and tob.	405	-0.0014***	-0.0003	0.0002***	-0.061	-0.011
		(0.0005)	(0.0003)	(0.0001)		
Text, text. prod, Leath.	395	-0.0011	0.0009	0.0006	-0.036	0.029
		(0.0010)	(0.0008)	(0.0008)		
Wood and prod. of wood	393	-0.0073**	-0.0015	0.0010***	-0.205	-0.042
		(0.0031)	(0.0012)	(0.0002)		
Pulp, pap., print. and publ.	412	-0.0036***	0.0014**	-0.0004***	-0.080	0.031
		(0.0011)	(0.0007)	(0.0001)		
Man. of coke & petr.	353	-0.0139*	-0.0119***	0.0004	-0.020	-0.020
		(0.0079)	(0.0043)	(0.0005)		
Chemicals	405	-0.0016	-0.0046**	-0.0012***	-0.014	-0.041
		(0.0031)	(0.0020)	(0.0004)		
Rubber and plastics	403	-0.2638***	0.0068***	0.0004**	-3.937	0.101
		(0.0443)	(0.0012)	(0.0002)		
Non-metal. minerals	412	0.0015	-0.0040***	-0.0004**	0.014	-0.037
		(0.0024)	(0.0015)	(0.0002)		
Metals	405	-0.0017	-0.0006	-0.0003**	-0.029	-0.010
		(0.0018)	(0.0016)	(0.0001)		
Machinery nec	412	-0.0002	0.0007	-0.0002***	-0.010	0.042
		(0.0007)	(0.0006)	(0.0001)		
Office, acc.; elec. eng.	399	-0.0006	0.0006	-0.0001**	-0.039	0.037
		(0.0006)	(0.0005)	(0.0001)		
Transport Equipment	392	-0.0011*	0.0014***	-0.0004***	-0.065	0.080
		(0.0006)	(0.0005)	(0.0001)		
Manuf. nec; recycl.	400	-0.0002	-0.0006	0.0007***	-0.006	-0.024
		(0.0010)	(0.0008)	(0.0001)		
Sale & maint. of mot. vehic.	388	0.0415*	-0.0039**	0.0008***	1.145	-0.107
		(0.0240)	(0.0016)	(0.0001)		
Median		-0.0013	-0.0004	0.0000	-0.033	-0.010

Notes: [a]Own-price elasticity of energy as defined by Equation (A4). [b]Short run elasticity of energy intensity w.r.t. green knowledge stock as defined by Equation (8). All elasticities calculated using mean levels of inputs by sector: $s_{Ei} = \frac{1}{N}\sum_{i=1}^{n}\frac{P_{E,in}Q_{E,in}}{TCin}$ for sector i, averaged over countries 1...N. All estimations are by sector, based on the spec. with domestic, green stocks of granted patents, with country FE. Standard errors in parentheses. p***$\leq$ 0.01, p**$\leq$0.05, p*$\leq$0.1.

Table 5: Decomposition of long run change in energy intensity

Sector	$\hat{e}/e$	Budget	Substitution			Output	Technology		
			Capital	Labor	Energy		Tech$_G$	Tech$_{NG}$	Trend
1516	-0.010	0.324	0.001	-0.045	0.002	-0.328	-0.098	-0.040	0.174
1719	0.139	0.102	-0.009	-0.424	0.016	-0.129	-0.059	0.093	0.550
20	0.445	0.395	-0.005	-0.121	-0.021	-0.445	-0.142	-0.127	0.909
2122	-0.166	0.111	0.110	-0.138	0.009	-0.019	-0.113	0.116	-0.242
23	0.045	-0.021	-0.003	-0.028	-0.017	0.184	-0.029	-0.056	0.015
24	-0.299	-0.020	-0.046	-0.098	-0.003	0.255	-0.022	-0.117	-0.248
25	-0.231	-0.167	0.020	-0.209	0.019	-0.256	-0.140	0.301	0.201
26	-0.110	0.030	-0.005	-0.100	-0.020	0.166	0.023	-0.102	-0.102
2728	-0.182	0.002	0.003	-0.161	-0.042	0.232	-0.072	-0.032	-0.112
29	-0.157	-0.058	0.003	-0.140	-0.021	0.279	-0.023	0.123	-0.320
3033	-0.360	-0.154	0.019	-0.107	0.069	-0.084	-0.025	0.028	-0.108
3435	-0.245	-0.022	0.080	0.002	-0.016	0.133	-0.103	0.222	-0.540
3637	0.335	1.708	-0.040	-0.364	-0.060	-1.943	-0.021	-0.142	1.195
50	-0.162	0.849	-0.040	-0.235	0.071	-1.233	0.050	-0.144	0.521
Median	-0.160	0.016	-0.001	-0.129	-0.009	-0.052	-0.044	-0.036	-0.043

Notes: Results for the decomposition from 1980 to 2005 (median impact across countries). Only countries with non-missing values over the entire sample period are included, thus our sample of countries can vary across sectors.

5 Conclusion

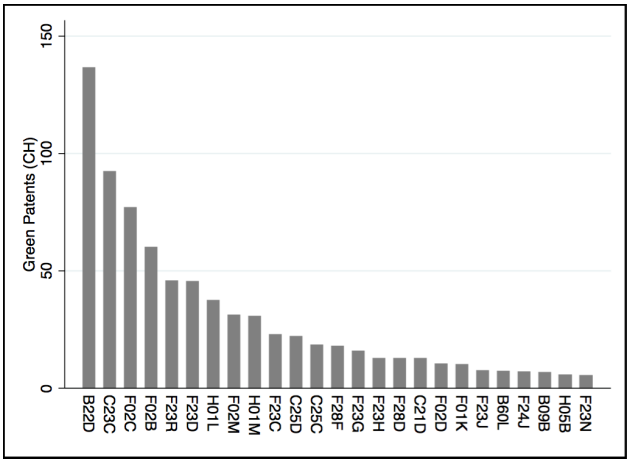
This paper was the first attempt to quantify the impact of green innovation on energy intensity of industries using patent statistics in a multi-sector, multi-country setting. The main purpose of our results is to inform policymakers about the magnitude of the impact of green innovation on energy intensity across industrial sectors, and to contribute to the empirical body of evidence in favour of policies supporting green R&D: by matching sector-specific green knowledge stocks with input cost functions based on EU-KLEMS, we find that green innovation is energy-saving in a majority of industries, with a median elasticity of -0.03. Hence, a 1% increase in green patenting activities in a given sector is associated with a 0.03% decline in energy intensity at the median. Interestingly, we find a statistically significant impact in all energy intensive industries. This result could be interesting from a policymaking perspective: energy consumption could be reduced through innovation in industries where it is largest, which would thus translate in large gains at the aggregate level.

Finally, a decomposition exercise has suggested that roughly half of the decrease in predicted energy intensity is caused by changes in input prices and half is caused by changes in production technologies. This sizable result highlights the importance of innovation in decreasing energy intensity. Within the estimated contribution of technology, 35% can be attributed to green patented innovation, 30% to non-green innovation, and 35% to autonomous technical change.

We close by suggesting several extensions for future work. First, future contributions could include more factors potentially affecting energy consumption, such as energy policies for example. Although these are implicitly captured by the price variables in our estimated equations, inasmuch as they influence input demand, incorporating explicitly variables measuring energy policies could help identifying the role of policymaking more clearly. Second, our measure of elasticity captures the direct impact of green patents. Long term elasticities are likely to be of greater magnitude as effects accumulate through time. A more complete analysis of these long term effects remains an important research question, but would require to measure adequately spillover effects, both across industries and time, for example in a general equilibrium setting.

6 Interpretations and conclusions for Switzerland

Figure 6: Green patents in Switzerland by IPC classification



This section presents additional insights for Switzerland. Energy efficiency is at the core of the energy strategy in Switzerland, materialized in the *Energy Strategy 2050* currently discussed in the Parliament. The strategy contains specific provisions to improve energy efficiency over a broad spectrum of activities, namely in construction, industry and services, mobility and electrical appliances. These instruments include fiscal incentives, as well as other types of policies.

In this context, this paper is the first attempt to quantify the impact of green innovation on energy intensity of industries using patent statistics in a multi-sector, multi-country setting across OECD countries, including Switzerland. The main purpose of our results is to inform policymakers about the magnitude of the impact of green innovation on energy intensity across industrial sectors. Our findings contribute to the empirical body of evidence in favour of policies supporting green R&D, such as research subsidies for example: we find that green innovation is energy-saving in a majority of industries, with a median elasticity of -0.03. Hence, a 1% increase in green patenting activities in a given sector is associated with a 0.03% decline in energy intensity at the median. Furthermore, roughly half of the decrease in energy intensity across OECD countries from 1975 to 2005 is found to be caused by changes in input prices and half by changes in production technologies. This sizable result again highlights the importance of innovation in decreasing energy intensity. Within the estimated contribution of technology, 35% can be attributed to green patented innovation, 30% to non-green innovation, and 35% to autonomous technical change.

Switzerland is known as a major innovator, particularly when taking its limited size into account. Using our data sample, and as shown in Figure 2 the country is ranked 6th largest innovator in terms of total green patents after Japan, the United States, Germany, France and Great Britain.[32] Combined with our statistically significant estimates for the impact of green innovation on energy intensity, this would translate into a significant decrease in energy consumption throughout our sample period.

In terms of composition, by industry of use, green innovation in Switzerland seems to be comparable to the innovation landscape observed in OECD countries: Switzerland is found to innovate more intensively in Machinery and Equipment (NACE 29) and in Metals (NACE 27t28), which is line with the tendency observed in other OECD countries, as presented in Section 3.

Figure 7 presents the cost share of each input by sector for Switzerland as compared to the OECD average. These variables are the main dependent variable of our estimates, on which our measure of energy intensity is based. Interestingly, sectors are on average more capital intensive in Switzerland, and use relatively less materials. In terms of energy, all industrial sectors in our sample are less energy intensive in Switzerland than the OECD average. The most striking differences are observed for sectors 24 (Chemicals) and 26 (Non-metallic minerals). Although this could reflect more energy-efficient production techniques, this could also be caused by compositional differences within industrial classes between Switzerland and the average of industrialized countries. NACE Sector 24 (Chemicals), for example, includes a diverse set of activities such as pharmaceuticals, or heavy chemical products. Some of the largest pharmaceutical conglomerates worldwide are based in Switzerland, such that pharmaceutical products amount to 3.3% of GDP and 32% of Swiss exports in 2011, and thus account for the majority of production in NACE Sector 24. One could expect these types of activities to be less energy intensive than heavy, less specialized chemical processes.

Figure 8 shows the evolution of the cost share of energy of Switzerland as compared to the OECD average. As can be seen, energy cost shares in Switzerland have experienced a decrease between 2001 and 2004, whereas the average cost shares across OECD countries remained mostly

[32] In a study by Ley et al. (August 2013), Switzerland ranks at the 10th position in terms of its relative share in total green patents and 17th in terms of the ratio of green patents to other patents. The authors interpret these results as suggesting that Swiss firms invest relatively little in green technologies. The difference with our results could be explained by the fact that we look at triadic patents, i.e. high-value patents and by the fact that we focus on the manufacturing sector only.

Figure 7: Cost shares by sector: OECD vs. CH

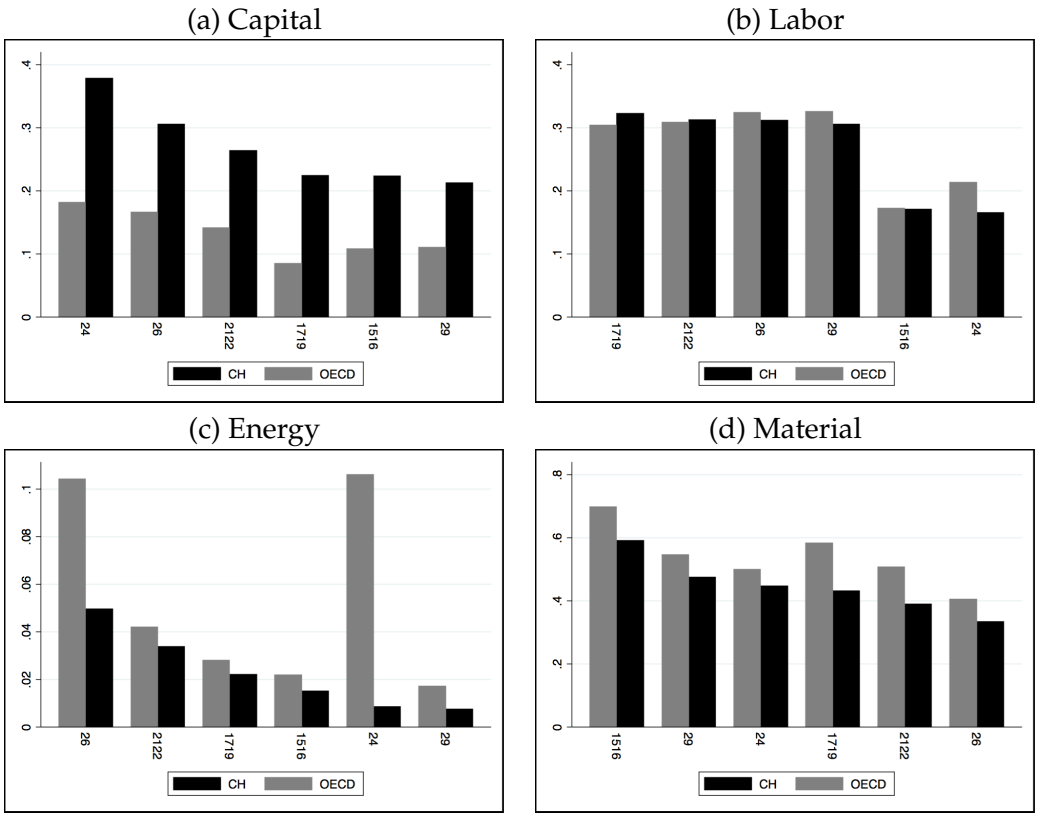
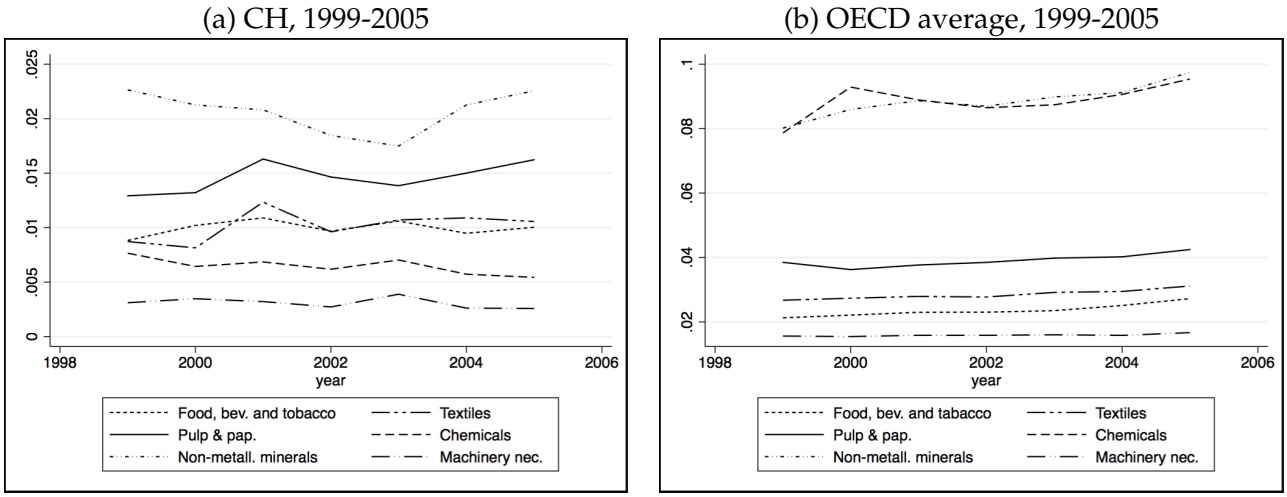


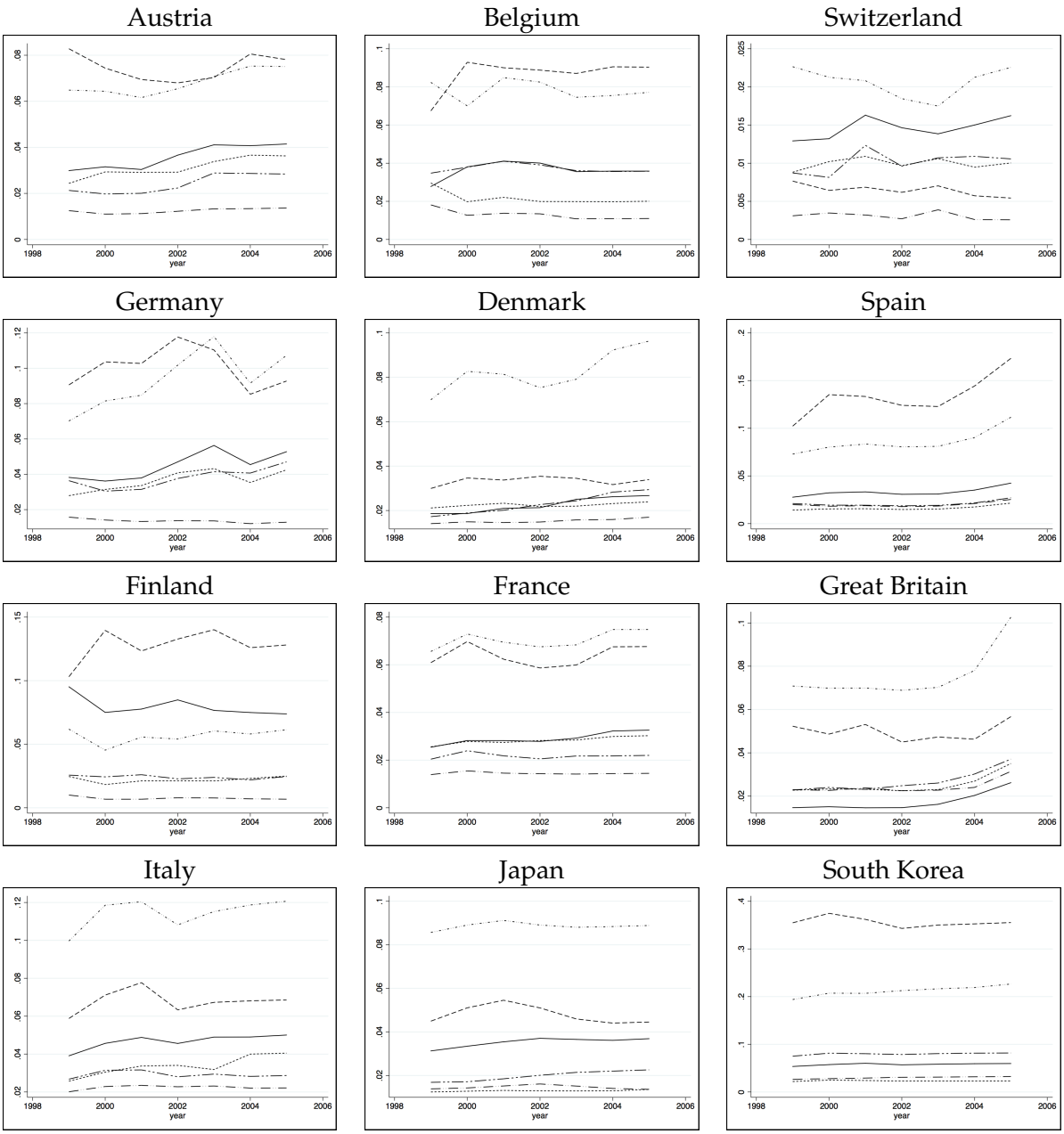
Figure 8: Cost share of energy



flat.

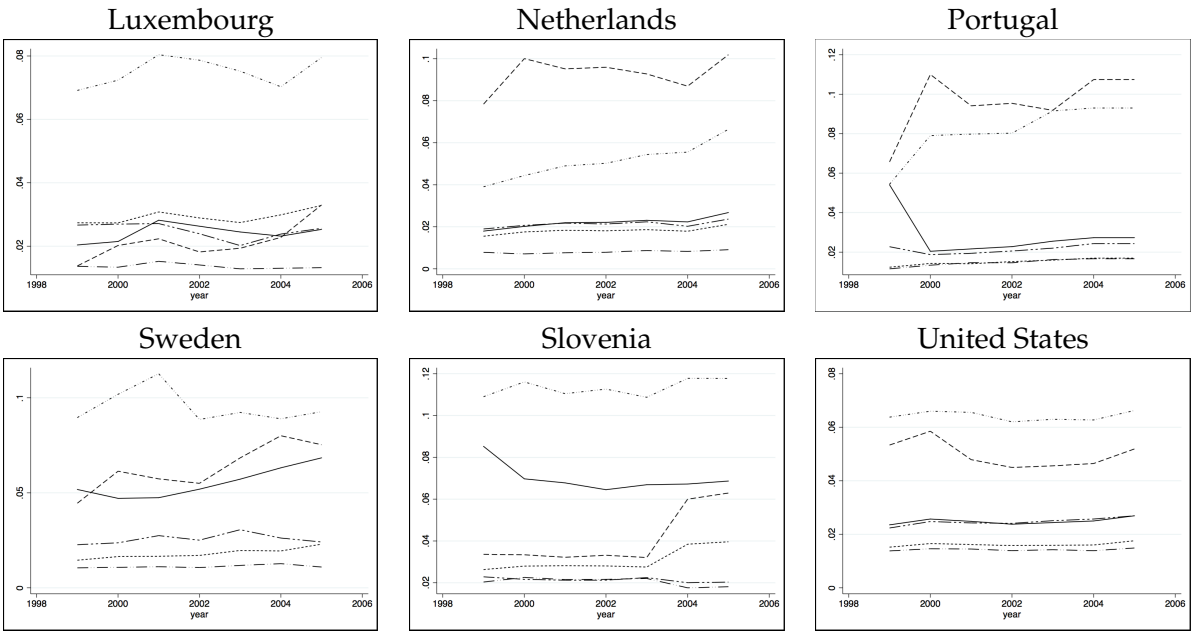
Figures 9 and 10 plot the evolution of the cost shares of energy for different sectors (see sector

Figure 9: Cost share of energy by sector: OECD vs. CH



legend in Figure 8) for various OECD countries. Overall, these descriptive statistics suggest that most OECD countries have seen an increase in the cost share of energy in the 2002-2005 period – except in the case of Germany, and, to a certain extent, Japan – even if there remains important differences across countries. This contrasts with the case of Switzerland.

Figure 10: Cost share of energy by sector: OECD vs. CH (continued)



Although this result could be generated by differences in data measurement, overall, graphical evidence highlights structural differences between Switzerland and other OECD countries, as reflected by the input mix in each industry, and by the evolution of the share of costs attributable to energy. If any, our analysis for Switzerland points towards important heterogeneity in production structure between countries, which is captured in our estimated equations by the inclusion of country fixed effects. Our empirical estimates present an average impact across OECD countries, sector by sector, which prioritizes cross-sectoral heterogeneity at the expense of cross-country heterogeneity. Although we could not run separate regressions for Switzerland alone, and thereby recover specific elasticity measures, the importance of green innovation combined with an important decrease in the cost share of energy points towards a sizeable impact of green innovation on energy intensity.

In order to make conclusive arguments however, further research would require following Switzerland through a longer time period, so as to observe whether this decrease in energy cost share is caused, for example, by a longer period requirement for technology adoption – innovation would trigger energy intensity improvements, but with a greater period lag. However, as men-

tioned previously, empirical estimates tailored for Switzerland would require access to a larger and more extensive dataset, with a larger coverage of sectors and of time periods.

Despite these limitations, our results for the broader set of OECD countries including Switzerland have implications for Swiss policymaking. In the context of Switzerland, our results underline that policy initiatives aiming to encourage green innovation such as the Action plan for coordinated energy research which sets innovative research and development as one of the main pillars of the new energy strategy will effectively contribute to improve the energy efficiency of production processes in Swiss industries. In addition, as we also find that rising energy prices induce a substitution away from energy towards other inputs, public policies putting a higher price on energy, such as current proposals in the *Energy Strategy 2050*, are also likely to yield important energy efficiency gains.

A Parameter Derivation

A.1 Elasticities of energy intensity w.r.t. technology

$$\epsilon_{E,G} = \frac{\partial ln(E/Y)}{\partial lnG} = \frac{\partial (E/Y)}{\partial lnG}\frac{Y}{E} = \frac{\partial((P_Y/P_E)s_E)}{\partial lnG}\frac{Y}{E}$$
$$= \frac{\partial s_E}{\partial lnG}\frac{Y}{E}\frac{P_Y}{P_E} = \beta_{EG}\frac{P_Y Y}{P_E E} = \beta_{EG}\frac{1}{s_E} = \frac{\beta_{EG}}{s_E}$$

A.2 Elasticities of substitution

We first derive Allen partial elasticities of substitution (σ_{ii} and σ_{ij}) from the coefficients estimated in Equation (6):

$$\sigma_{ij} = \sigma_{ji} = 1 + \frac{\beta_{ij}}{s_i s_j}, \quad i \neq j \tag{A1}$$

$$\sigma_{ii} = \frac{\beta_{ii} + s_i^2 - s_i}{s_i^2} \tag{A2}$$

Since AES cannot be easily interpreted in the case of more than two inputs (Blackorby and Russell, 1989; Thompson and Taylor, 1995), we calculate cross- and own-price elasticities from the estimated AES, following (Berndt, 1991):[33]

$$\eta_{ij} = \sigma_{ij} s_j = \frac{\beta_{ij} + s_i s_j}{s_i} = \frac{\beta_{ij}}{s_i} + s_j, \quad i \neq j \tag{A3}$$

$$\eta_{ii} = \sigma_{ii} s_i = \frac{\beta_{ii} + s_i^2 - s_i}{s_i} = \frac{\beta_{ii}}{s_i} + s_i - 1 \tag{A4}$$

The cross-price elasticity measures the change in the quantity of input x_i caused by a change of the price of input j (for instance, in the case of energy and labor, $\eta_{E,PL} = \frac{\partial lnE_i}{\partial lnp_L}$ where E is energy demand) and thus has a direct economic interpretation. Substitutability/complementarity between inputs can be interpreted as follows. Based on cross-price elasticities, input i is a substitute (complement) for input j if $\eta_{ij} > (<)\ 0$. Standard errors for the estimated parameters have

[33] The computation of the variance of each elasticity can be found in A.

been reconstructed following Binswanger (1974) or Koetse et al. (2008) by using the Delta method (Greene, 2000). Standard errors of elasticities are calculated as follows:

$$V(\eta_{ij}) = V\left(\frac{\beta_{ij}}{S_i} + S_j\right) = \frac{1}{S_i^2} V(\beta_{ij})$$

$$SE(\eta_{ij}) = \sqrt{V(\eta_{ij})} = \frac{1}{S_i} SE(\beta_{ij})$$

$$SE(\eta_{ii}) = \sqrt{V(\eta_{ii})} = \frac{1}{S_i} SE(\beta_{ii})$$

A.3 Additional tables and graphs

Table A1: Green IPC codes in sample

IPC	Description	IPC	Description
B09B	Disp. of solid waste	F02P	Combustion engine: ignition
B22D	Casting of metals	F03B	Hydro
B60K	Motor Vehicle: Arr. of Propuls. units.	F03D	Wind
B60L	Motor Vehicle: Prop. of electr. vehicles	F03G	Mechanical-power-producing mechanisms
B60R	Motor Vehicle: Fitting	F23B	Combustion apparatus
B60S	Motor Vehicle: Cleaning	F23C	Combustion apparatus
B60W	Motor Vehicle	F23D	Combustion apparatus
C02F	Methane capture	F23G	Waste
C04B	Cement	F23H	Combustion apparatus
C10G	Prod. of liquid hydrocarbon mixtures	F23J	Combustion apparatus
C10J	Prod. of gases containing carbon monoxide and hydrogen	F23K	Combustion apparatus
C10K	Modifying the chemical composition of combustible gases	F23L	Heating of air supplied for combustion
C10L	Waste	F23M	Combustion apparatus
C12M	Methane capture	F23N	Combustion apparatus
C21D	General methods or devices for heat treatment	F23Q	Combustion apparatus
C22B	Production or refining of metals	F23R	Combustion apparatus
C23C	Coating of metallic material	F24D	Heating
C25C	Processes for the electrolythic production	F24F	Heating
C25D	Processes for the electrolythic production	F24J	Solar
D21C	Regeneration of pulp liquors	F25B	Heating
E02B	Hydro	F26B	Solar
E04B	Insulation	F28B	Steam or vapour condensers
E06B	Insulation	F28C	Heat exchange apparatus
F01K	Plants characterised by more than one engine	F28D	Heat exchange apparatus nec
F02B	Combustion engine: intern. comb.	F28F	Heat exchange in general
F02C	Combustion engine: gas turbine	F28G	Heat exchange in general
F02D	Combustion engine: controlling comb.	H01J	Lighting
F02F	Combustion engine: cylinders for comb.	H01L	Semiconductor devices
F02G	Combustion engine: comb. products	H01M	Fuel cells; Manufacture thereof
F02K	Combustion engine: jet prop. plants	H02N	Solar
F02M	Combustion engine in general	H05B	Lighting
F02N	Combustion engine: starting of comb.		

Notes: Only the first 4 digits of the codes are presented for brevity. A more disaggregated list of technologies will be provided on request.

B Sample

Table B1: Descriptive statistics of the dataset

Variable	Code	Units	Obs	Mean	Std. Dev.	Min	Max
			Green patent stocks				
Year			17′980	1990	10.4	1975	2005
Pat Stock	Triadic	Patent number	10′540	18.8	90.35	0.00	1′339
			Value of output and input compensation				
Y	GO	cst. mil. LCU	8′490	2′142′898	9′649′104	0.00	$1.92*10^8$
K	CAP	cst. mil. LCU	8′490	267′804	1′250′149	0.00	$2.80*10^7$
L	LAB	cst. mil. LCU	8′490	364′597	1′518′297	0.00	$2.46*10^7$
E	IIE	cst. mil. LCU	6′922	167′778	1′146′254	0.00	$3.00*10^7$
M	IIM	cst. mil. LCU	6′922	1′348′215	5′869′449	0.00	$1.07*10^8$
			Input quantity indexes				
Y_QI	GO_QI	Index	8′490	0.895	0.363	0.006	5.090
K_QI	CAP_QI	Index	8′028	0.889	0.846	0.003	28.99
L_QI	LAB_QI	Index	6′748	1.050	0.311	0.054	4.770
E_QI	IIE_QI	Index	6′341	0.999	0.468	0.008	63.54
M_QI	IIM_QI	Index	6′341	0.926	0.412	0.006	9.120
			Price indexes				
py		Index	8′608	0.797	0.359	0.03	4.435
pk		Index	8′104	1.049	184.1	0.00	36.24
pl		Index	6′888	0.832	60.35	0.03	5.537
pe		Index	6′484	0.993	101.9	0.12	27.88
pm		Index	8′952	0.935	2.404	0.07	97.32
			Total costs and cost shares				
TC		cst. mil. LCU	9′635	2′290′811	9′293′264	0.0000	$1.6*10^8$
sk		Percentage	6′911	0.121	0.065	0.0000	0.589
sl		Percentage	6′911	0.286	0.123	0.0080	0.788
se		Percentage	6′911	0.087	0.180	0.0002	0.973
sm		Percentage	6′911	0.505	0.164	0.0002	0.858

Notes: Input compensation and Value of output are in current mill. local currency. Quantities are indexes ($1995 = 1$). Price are calc. from normalized input compensation and indexes of quantities ($1995 = 1$). Cost shares are calculated from Total Costs (TC), defined as the sum of all input compensation.

C Additional Parameter Estimates

Table C1: Coefficient on price indexes and output level, cost share of energy

Sector	β_{EE}	β_{EK}	β_{EL}	β_{EY}
Food, beverages and tobacco	0.0050***	-0.0029***	-0.0021**	-0.0031***
	(0.0008)	(0.0008)	(0.0009)	(0.0010)
Textiles, textile products,leather	0.0178***	0.0001	-0.0178***	-0.0034***
	(0.0017)	(0.0007)	(0.0016)	(0.0011)
Wood and products of wood and cork	0.0098***	-0.0042***	-0.0056***	0.0036**
	(0.0021)	(0.0009)	(0.0020)	(0.0018)
Pulp, paper and paper prod., print. and publish.	0.0201***	-0.0096***	-0.0105***	0.0025
	(0.0021)	(0.0015)	(0.0022)	(0.0018)
Man. of coke, refined petrol. prod. and nucl. fuel	0.0651***	-0.0433***	-0.0218***	0.0531***
	(0.0035)	(0.0027)	(0.0020)	(0.0049)
Chemicals	0.0389***	-0.0244***	-0.0146***	0.0217***
	(0.0028)	(0.0019)	(0.0019)	(0.0038)
Rubber and plastics	0.0368***	-0.0146***	-0.0221***	0.0012
	(0.0033)	(0.0017)	(0.0032)	(0.0025)
Non-metallic minerals	0.0478***	-0.0264***	-0.0214***	0.0041
	(0.0030)	(0.0022)	(0.0026)	(0.0029)
Metals	0.0314***	-0.0107***	-0.0207***	0.0083***
	(0.0018)	(0.0011)	(0.0018)	(0.0013)
Machinery nec.	0.0059***	-0.0003	-0.0056***	0.0033***
	(0.0009)	(0.0005)	(0.0010)	(0.0006)
Office, account.; electric., medic. and precis. engin.	0.0056***	-0.0038***	-0.0018**	0.0014**
	(0.0007)	(0.0005)	(0.0007)	(0.0006)
Transport equipment	0.0030***	-0.0025***	-0.0005	0.0023***
	(0.0005)	(0.0003)	(0.0006)	(0.0007)
Manufacturing nec; recycling	0.0092***	0.0014*	-0.0106***	-0.0055***
	(0.0013)	(0.0008)	(0.0013)	(0.0013)
Sale, maint. of motor vehic.; retail sale of fuel	0.0170***	-0.0055***	-0.0115***	-0.0092
	(0.0016)	(0.0009)	(0.0016)	(0.0015)

Notes: Estimates by sector, based on the spec. with domestic, green stocks of granted patents, with country FE. Sectors 51, 52, 60t63, 64, 70, 71t74 missing because of zero green capital stock (see conc. table for details). Standard errors in parentheses. p***$\leq$ 0.01, p**$\leq$0.05, p*$\leq$0.1.

Table C2: Cross-price elasticities of substitution for energy input

	Energy η_{EE}	Capital η_{EK}	Labor η_{EL}
Food, beverages and tobacco	-0.765	0.007	0.114
	(0.036)	(0.034)	(0.040)
Textiles, textile products, leather	-0.370	0.118	-0.283
	(0.057)	(0.024)	(0.053)
Wood and products of wood and cork	-0.656	0.015	0.089
	(0.061)	(0.025)	(0.060)
Pulp, paper and paper prod., print. and publish.	-0.508	-0.056	0.097
	(0.048)	(0.033)	(0.050)
Man. of coke, refined petrol. prod. and nucl. fuel	-0.209	0.055	0.014
	(0.005)	(0.004)	(0.003)
Chemicals	-0.548	-0.024	0.101
	(0.027)	(0.017)	(0.019)
Rubber and plastics	-0.472	-0.027	0.016
	(0.052)	(0.028)	(0.048)
Non-metallic minerals	-0.448	-0.063	0.130
	(0.028)	(0.020)	(0.024)
Metals	-0.418	-0.046	-0.070
	(0.033)	(0.018)	(0.033)
Machinery nec	-0.666	0.113	0.020
	(0.053)	(0.031)	(0.060)
Office, account.; electric., medic. and precis. engin.	-0.610	-0.101	0.198
	(0.050)	(0.034)	(0.050)
Transport equipment	-0.845	-0.057	0.277
	(0.033)	(0.021)	(0.037)
Manufacturing nec; recycling	-0.625	0.185	-0.064
	(0.054)	(0.032)	(0.052)
Sale, maint. of motor vehic.; retail sale of fuel	-0.440	0.071	0.137
	(0.048)	(0.022)	(0.051)

Notes: All elasticities calculated using mean levels of cost shares by sector: $s_{Ei} = \frac{1}{N}\sum_{i=1}^{n}\frac{P_{E,in}Q_{E,in}}{TCin}$ for sector i, averaged over countries 1...N.

References

Acemoglu, D. (2002) "Directed technical change," *Review of Economic Studies*, 69, pp. 781–809.

Acs, Z. and D. Audretsch (1989) "Patents innovative activity," *Eastern Economic Journal*, 15(4), pp. 373–376.

Ahmad, S. (1966) "On the theory of induced innovation," *The Economic Journal*, 76, pp. 344–357.

Ang, B. and F. Liu (2001) "A new energy decomposition method: perfect in decomposition and consistent in aggregation," *Energy*, 26, pp. 537–548.

Apostolakis, B. E. (1990) "Energy – capital substitutability/complementarity: the dichotomy," *Energy Economics*, 12, 1, pp. 48–58.

Arnberg, S. and T. B. Bjorner (2007) "Substitution between energy, capital and labour within industrial companies: A micro panel data analysis," *Resource and Energy Economics*, 29(2), pp. 122–136.

Berndt, E. R. (1991) *The Practice of Econometrics*: Addison-Wesley Publishing Company, Reading, Mass.

Berndt, E. R. and D. O. Wood (1975) "Technology, prices, and the derived demand for energy," *The Review of Economics and Statistics*, 57, 3, pp. 259–268.

Binswanger, H. P. (1974) "A cost function approach to the measurement of elasticities of factor demand and elasticities of substitution," *American Journal of Agricultural Economics*, 56, 2, pp. 377–386.

Blackorby, C. and R. Russell (1989) "Will the real elasticity of substitution please stand up? (A comparison of the Allen/Uzawa and Morishima elasticities)," *The American Economic Review*, 79, 4, pp. 882–888.

Christensen, L., D. W. Jorgenson, and J. Lawrence (1973) "Transcendental logarithmic production frontiers," *The Review of Economics and Statistics*, 55, pp. 28 – 45.

Comanor, W. and F. Scherer (1969) "Patent statistics as a measure of technical change," *Journal of Political Economy*, 77(3), pp. 392–398.

Dechezlepretre, A., M. Glachant, I. Hascic, N. Johnstone, and Y. Meniere (2011) "Invention and transfer of climate change-mitigation technologies: A global analysis," *Review of Environmental Economics and Policy*, 5, pp. 109–130.

Dernis, H. and M. Khan (2004) "Triadic patent families methodology,"Technical report, OECD Science, Technology and Industry Working Papers.

Evenson, R., J. Putnam, and S. Kortum (1991) "Estimating patent counts by industry using the yale-canada concordance.," *Final Report to the National Science Foundation*.

Fisher-Vanden, K., G. H. Jefferson, H. Liu, and Q. Tao (2004) "What is driving china's decline in energy intensity?" *Resource and Energy Economics*, 26, pp. 77–97.

Greene, W. (2000) *Econometric Analysis*: Upper Saddle River, NJ: Prentice Hall.

Griliches, Z. (1990) "Patent statistics as economic indicators: A survey," *Journal of Economic Literature*, 28(4), pp. 1661–1707.

Hagedoorn, J. and M. Cloodt (2003) "Measuring innovative performance: Is there an advantage in using multiple indicators?" *Research Policy*, 32, pp. 1365–1379.

Haller, S. and M. Hyland (2014) "Capital–energy substitution: Evidence from a panel of irish manufacturing firms," *Energy Economics*, 45, pp. 501–510.

Hesse, D. M. and H. Tarkka (1986) "The demand for capital, labor and energy in european manufacturing industry before and after the oil price shocks," *The Scandinavian Journal of Economics*, 88, 3, pp. 529–546.

Hicks, J. R. (1932) *The Theory of Wages*: London: Macmillan.

Hunt, L. C. (1986) "Energy and capital: substitutes or complements? A note on the importance of testing for non-neutral technical progress," *Applied Economics*, 18, 7, pp. 729–735.

IEA (2012) "Energy technology perspectives," *International Energy Agency, Paris*.

Jaffe, A. B., M. Trajtenberg, and R. Henderson (1993) "Geographic localization of knowledge spillovers as evidenced by patent citations," *The Quarterly Journal of Economics*, 108, pp. 577–598.

Jaffe, A. B. and K. Palmer (1997) "Environmental regulation and innovation: A panel data study," *The Review of Economics and Statistics*, pp. 610–619.

Johnstone, N., I. Hascic, and D. Popp (2010) "Renewable energy policies and technological innovation: Evidence based on patent counts," *Environmental and Resource Economics*, 45, pp. 133–155.

Jorgenson, D. W. and B. Fraumeni (1981) *Modeling and Measuring Natural Resource Substitution*, Chap. Relative Prices and Technical Change, pp. 17 – 47: MIT Press: Cambridge.

Kim, J. and E. Heo (2013) "Asymmetric substitutability between energy and capital: Evidence from the manufacturing sectors in 10 OECD countries," *Energy Economics*, 40, pp. 81–89.

Koetse, M. J., H. L. F. de Groot, and R. Florax (2008) "Capital-energy substitution and shifts in factor demand: A meta-analysis," *Energy Economics*, 30, 5, pp. 2236–2251.

Ley, M., T. Stucki, and M. Woerter (August 2013) "The impact of energy prices on green innovation," *KOF Working Papers*, 340.

Lybbert, T. J. and N. J. Zolas (2014) "Getting patents and economic data to speak to each other: An 'algorithmic links with probabilities' approach for joint analyses of patenting and economic activity," *Research Policy*, 43, 3, pp. 530–542.

Ma, H., L. Oxley, J. Gibson, and B. Kim (2008) "China's energy economy: Technical change, factor demand and interfactor/interfuel substitution," *Energy Economics*, 30, 5, pp. 2167–2183.

Martinez, C. (2010) "Insight into different types of patent families,"Technical report, STI Working Paper 2010/2.

Mohler, L. and D. Mueller (2011) "Substitution elasticities in swiss manufacturing," *Report for the Swiss Federal Office of Energy (SFOE)*.

Mulder, P., H. L. F. de Groot, and B. Pfeiffer (2014) "Dynamics and determinants of energy intensity in the service sector: A cross-country analysis, 1980–2005," *Ecological Economics*, 100, pp. 1–15.

Mulder, P. and H. L. de Groot (2012) "Structural change and convergence of energy intensity across oecd countries, 1970 – 2005," *Energy Economics*, 34, 6, pp. 1910–1921.

Nesta, L., F. Vona, and F. Nicolli (2014) "Environmental policies, competition and innovation in renewable energy," *Journal of Environmental Economics and Management*, 67, pp. 396–411.

Newell, R. G., A. B. Jaffe, and R. N. Stavins (1999) "The induced innovation hypothesis and energy-saving technological change," *The Quarterly Journal of Economics*, 114, 3, pp. 941–975.

OECD ed. (2009) *OECD Patent Statistics Manual*: OECD.

O'Mahony, M. and M. P. Timmer (2009) "Output, input and productivity measures at the industry level: The EU KLEMS database," *The Economic Journal*, 119, 538, pp. 374–403.

Popp, D. (2001) "The effect of new technology on energy consumption," *Resource and Energy Economics*, 23, 3, pp. 215–239.

——— (2002) "Induced innovation and energy prices," *The American Economic Review*, 92, 1, pp. 160–180.

——— (2005) "Lessons from patents: Using patents to measure technological change in environmental models," *Ecological Economics*, 54, pp. 209–226.

Porter, M. and C. Van der Linde (1995) "Toward a new conception of the environment-competitiveness relationship," *Journal of Economic Perspectives*, 9, pp. 97 – 118.

Shephard, R. (1953) *Cost and production functions*: Princeton University Press.

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, pp. 340–356.

Sue Wing, I. (2008) "Explaining the declining energy intensity of the u.s. economy," *Resource and Energy Economics*, 30, pp. 21–49.

Thompson, H. (2006) "The applied theory of energy substitution in production," *Energy Economics*, 28, 4, pp. 410–425.

Thompson, P. and T. G. Taylor (1995) "The capital-energy substitutability debate: A new look," *The Review of Economics and Statistics*, 77, 3, pp. 565–569.

Verdolini, E. and M. Galeotti (2011) "At home and abroad: An empirical analysis of innovation and diffusion in energy technologies," *Journal of Environmental Economics and Management*, 61, pp. 119 – 134.

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, pp. 47–62.

Welsch, H. and C. Ochsen (2005) "The determinants of aggregate energy use in west germany: factor substitution, technological change, and trade," *Energy Economics*, 27, pp. 93–111.