Explaining Trends in Aggregate and Sectoral Energy Intensity: The Dynamics of the Sectoral Intensity Gap

Claudio Baccianti*

9th May 2014

Abstract

Despite the large literature about trends in aggregate energy productivity, little attention has been paid on what drives the gap in sectoral energy intensity over time. Data show some puzzling features, as the faster improvement in energy productivity in services compared to the manufacturing sector in some countries. Here I reconcile theory with empirical evidence and suggest extensions to have a better model fit to stylized facts. Finally, I evaluate the possibility and implications of the faster energy productivity growth in manufacturing, which might lead to lower energy intensity than services.

Keywords: energy intensity, structural transformation, multi sector model, directed technological change

JEL Classification: Q43,O14,O4

*Centre for European Economic Research (ZEW) and Tilburg University. Address: L7,1 68161 Mannheim, Germany. Email: baccianti@zew.de.

1 Introduction

The challenge of expanding the renewable energy share in the energy mix still seems overwhelming, despite massive public and private investment worldwide and fast technological advancements. Recent data show that in 2011 the share of renewable energy over the total world energy consumption was 13 percent (IEA 2013a) but modern technologies as solar and wind power account for no more than 7 percent. The ambitious target of reducing the dependence on fossil fuels is only likely to be attained if total energy demand growth eases. Therefore, an effective climate change strategy should give an important role to energy productivity. The International Energy Agency has called energy efficiency the world's "first fuel" (IEA 2013b). Energy efficiency is in fact one of the three pillars of the European Union's "20-20-20" climate policy package, with a target of 20% increase in EU's aggregate energy productivity by 2020.

Energy productivity is the inverse of energy intensity, the subject of several studies in the field of environmental and energy economics in the last decades. In spite of the large amount of work done so far on such an important topic, our understanding of aggregate energy intensity is far from being satisfying. Many studies have a purely descriptive purpose, i.e. decomposition analysis (Ang and Zhang 2000, Ang 2004), and they are grounded on an accounting relationship about aggregate energy intensity, which has little to say about causality. Understanding the drivers of energy intensity is instead necessary to elaborate sound policy recommendations. In particular we need a theoretical framework that is able to explain aggregate and sectoral energy intensity and to account for the interactions between structural transformation and technological change. Cross-country heterogeneity in sectoral energy intensity trends is a very interesting feature of the data. Why in some countries the service sector improves energy efficiency faster than manufacturing? The divergence or convergence in the sectoral energy intensity gap is crucial to determine the benefits of sectoral reallocations in the long run.

Climate policy relies on the shift to a service-based economy to reduce economy-wide energy demand and emissions. This argument holds because it exists a rather large sectoral intensity gap in all countries that delivers a positive level effect on aggregate energy demand just by shifting value added generation from manufacturing to services. This type of economic transformation has helped developed countries to reduce emissions but developing countries, currently responsible for more than half of global energy demand, are instead going through the process of industrialization and will not be able in the near future to benefit from sectoral reallocation (i.e. Ma (2014) finds that sectoral reallocation has raised energy demand in China). Research to date has paid little attention on how the sectoral energy intensity gap evolves over time. The dynamics of energy intensity is very much depending on changes in sectoral Total Factor Productivity (TFP) and the manufacturing sector is characterized by a faster efficiency growth compared to services (i.e. Jorgenson and Timmer 2011). It is actually possible that the manufacturing sector catches up in terms of energy efficiency in the long run, but it depends on several factors that have to be carefully evaluated. As the static effect of sectoral reallocation depends on the current sectoral intensity gap, the dynamic effect depends on future patterns of sectoral energy intensities. Given the lack of past research on the topic, I attempt to screen existing theories and compare them to sectoral energy intensity data for developed countries. The first step is to develop a multi-sector model that embeds standard features from the structural transformation and directed technological change modelling literature. I present some potential model extension including endogenous TFP growth and distance-to-frontier theory.

The theoretical framework developed in this paper sheds light on the composition and technique effect discussed in the literature. In particular the model allows to pin down the exact technology effect, separate it from price effects and disentangle the biased and unbiased component. Biased technological change has in fact a very different effect from general productivity improvements when it benefits competing factors, i.e. labour, because it raises the marginal productivity and the relative demand for energy. The composition effect is beneficial to aggregate energy intensity if final demand is reallocated towards less energy intensive activities. But this level effect might negatively change the growth rate in aggregate energy efficiency because production might be shifted to sectors with low growing productivity and because these sectors are more labour intensive, redirecting research incentives away from energy through pressure on factor markets. This point is assessed with a numerical exercise.

The paper is organised as follows. Section 2 introduces a theoretical framework to analyse energy intensity and makes some critical remarks on decomposition analysis as used in energy economics. Section 3 is a presentation of the empirical evidence for aggregate and sectoral energy intensity in European countries. I discuss the potential of the basic theoretical framework to explain data facts. Section 4 shows the results of a numerical exercise. Section 5 summarizes the main results and presents the next steps.

2 Explaining Energy Intensity

The observation of different stages in a country's development path (see for instance Rostow (1990) and Kuznets and Murphy (1966)) gave ground to some important theories suggesting long-run regularities in natural resource use. The existence of such regularities is appealing for predicting future patterns and it is even more desirable if it embeds the optimistic view that the pressure on the environment eases with economic development, as for the Environmental Kuznets Curve (EKC) hypothesis . According to the EKC hypothesis the amount of pollution and natural resource use increases during the initial phase of industrialization but, as living standards and per capita income rise, economic pressures on the environment ease over time. This very general version of the EKC hypothesis is in fact only partially supported by empirical evidence - it holds only for a specific set of pollutants - and related studies so far have mostly focused on pollution and not on natural resource use. The Energy Ladder (EL) hypothesis is instead related to energy consumption and it is based on a similar intuition. Over the process of economic development, households and firms switch their primary source of energy from traditional biomass, including wood and agricultural and animal waste, into more modern energy sources as natural gas, oil and electricity (see Arseneau 2011). This theory aims to explain the energy mix but it has little to say about the amount of energy consumed. In fact, a theoretical framework that links energy intensity to economic development has not been proposed so far, despite the aboundant amount of empirical work on the topic.

In empirical work, decomposition analysis is one of the most popular methodologies used to study energy intensity trends (e.g. Ang and Zhang 2000, Ang 2004, IEA 2008 , Ma 2014). This strand of literature aims to disentangle some major drivers of energy efficiency by means of disaggregated data, such as sectoral data, and is based on a simple decomposition. The yearly flow of natural resource use R_t depends on the amount of environmental resource the economy uses to generate one unit of output, along with how many units of output Y_t are generated. So, $R_t = \frac{R_t}{Y_t} Y_t$. As we generally observe positive and steady growth in aggregate output over time, the change in aggregate intensity R_t/Y_t is the only channel of environmental moderation and the most interesting for research and policy. Energy demand is just a specific case of natural resource use. The economy-wide energy intensity is a complex concept for two reasons. Firstly, energy intensity is affected by technological and substitution effects, namely the technological characteristics, innovation, environmental regulation and the energy price dynamics. Secondly, it is defined at a high degree of aggregation and it is sensitive to changes in the economy's sectoral composition. In fact, an economy is generally composed of firms belonging to different sectors, heterogeneous with respect to energy intensity. By labelling each sector as $j = 1, ..., J$ the expression for aggregate energy intensity becomes:

$$\frac{E_t}{Y_t} = \sum_{j=1}^{J} \frac{E_{jt}}{Y_{jt}} \frac{Y_{jt}}{Y_t} = \sum_{j=1}^{J} \theta_{jt} \omega_{jt}. \tag{1}$$

If all sectors had the same energy intensity, so that $\theta_{jt} = \bar{\theta}$ for all j, then aggregate energy intensity would not be exposed to the effect of sectoral reallocation. Such case is never verified in the data.

Brock and Taylor (2005) call the percentage changes in the two terms in equation (1) the *composition* and *technique* effects, that together with the *scale* effect - changes in total output - are the major channels of environmental policy intervention to curb down energy demand.

2.1 Decomposition Analysis of Energy Intensity Trends

Studies based on index decomposition analysis offer evidence on past composition and technique effects for several countries (the latter is often renamed intensity effect). IEA (2008) finds a minor role of sectoral reallocation in energy intensity changes for IEA countries during the last 15 years. For most countries, the intensity effect gave the most important contribution in reducing energy demand and was in large part due to exceptional circumstances of the early 1990s. For instance, Canada and the United States were using relatively more energy per unit of produced output compared to other industrialized countries and experienced a technological catch-up over that period. Germany could benefit from the upgrade of old industrial technologies in the Eastern part of the country. At the same time, countries that were already on the efficiency frontier experienced small efficiency gains, as for Denmark and Japan. The study also offers a within-manufacturing analysis, showing that the composition effect in the industrial sector contributed to reduce energy use in US, Sweden, Korea, Japan, France and Finland.

The importance of the intensity effect is as well found in Mulder and de Groot (2012). In the same time frame of IEA (2008), among the most developed countries, the composition effect results to have played a major role only in UK, Denmark, Austria and Japan. De Cian et al. (2013) investigate aggregate and sectoral energy intensity trends for a group of developed and developing countries for the period 1995-2007. The authors employ a dataset including countries under different stages of development, as developed and the largest developing countries, which a more solid analysis of convergence in energy intensity. Moreover, data aggregation at the international level is able to measure more precisely the international composition effect, given that their dataset contains information for those developing countries who are the most important destinations for the outsourcing of manufacturing production in developed countries (i.e. China and Brasil). At the international level, the decomposition exercise finds that a large part of the energy intensity decline has been driven by the technique effect and sectoral reallocation had a minor role. However, country-level analysis shows a high degree of heterogeneity.

For some countries the results of decomposition analysis differ across studies, which might be due to differences in the level of sectoral disaggregation across datasets. The major weakness of decomposition analysis is the interpretation of the composition and technique effects because the analysis lacks of a supporting theoretical guidance.

2.2 Necessity of a Theoretical Framework

The composition and technique effects are not primitive variables nor independent If decomposition analysis finds relatively large technique effects, this results should be interpreted as the tendency within each sector to reduce energy intensity, but not necessarily by adopting more efficient technologies. In fact the technique effect captures very diverse drivers, such as the level of technology, including TFP and pure energy efficiency, sector-specific technical requirements on energy use (an automobile factory is more energy intensive than a law firm) and the optimal choice of energy use given relative energy prices. The last driver, that is the substitution effect, is the change in input mix for a given level of technological progress and does not involve the adoption of more efficient technologies. The long-run level of energy efficiency would stay unchanged if a temporary substitution effect were responsible for a large fraction of energy intensity variation.

I am going to present a simple two-sectors general equilibrium model to explain the point in more details.

2.3 A simple model of aggregate energy intensity

Understanding more precisely the composition and technique channels requires a general equilibrium model showing how the aggregate energy intensity relates to the exogenous underlying technology variables and the drivers of structural transformation. This section presents a stylized two-sector model with endogenous sectoral composition and endogenous biased technological change, without capital.

Demand I assume an infinitely living household with preferences over a sequence of final consumption bundles $\{C_t\}$ given by:

$$U = \sum_{t=0}^{\infty} \beta^t \ln C_t, \tag{2}$$

with a discount factor $0 < \beta < 1$. In each period the final consumption good is an aggregation of sectoral consumption goods as

$$C_t = \left[\pi \left(y_m\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\pi)\left(y_s + \bar{y}_s\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{3}$$

where $0 < \pi < 1$ is the consumption share parameter and the elasticity of substitution ε is assumed lower than unity. The constant $\bar{y}_s > 0$ is the non-homotheticity term that increases the expenditure share on services as income rises. Notice that the cross-price elasticity of substitution is different from ε because of $\bar{y}_s \neq 0$. As the household solves the standard problem of maximising (2) subject to (3) and a budget constraint (without savings), the ratio of expenditures on the manufacturing and service sector, ω_m and ω_s, is

$$\frac{\omega_m}{\omega_s} = \frac{1}{\psi_s}\left(\frac{\pi}{1-\pi}\right)^{\varepsilon}\left(\frac{p_m}{p_s}\right)^{1-\varepsilon}, \tag{4}$$

a function of the relative prices $\frac{p_m}{p_s}$, with $\psi_s = \frac{y_s}{y_s+\bar{y}_s} \leq 1$.

Production The production side of the economy is divided into two sectors, energy-intensive industry m and the more labour-intensive services s, supplying goods y_m and services y_s to final consumers. Firms employ energy and labour with a constant elasticity of substitution production function with heterogeneous factor shares. Intermediate goods are assumed use a constant fraction of total output and, thanks to this assumption (cfr Herrendof et al. 2013) a sectoral value added function exists (having energy instead of capital). The production function for sector j, $j \in \{m, s\}$, is

$$y_{jt} = \Phi_{jt}\left[\nu_j \left(A_{Et}E_{jt}\right)^{\frac{\sigma_j - 1}{\sigma_j}} + (1-\nu_j)\left(A_{Lt}L_{jt}\right)^{\frac{\sigma_j - 1}{\sigma_j}}\right]^{\frac{\sigma_j}{\sigma_j - 1}}, \tag{5}$$

where E_j and L_j are respectively the physical units of energy and labour used in production and A_{Et} and A_{Lt} measure the efficiency units of energy and labour at time t. The coefficients A_{Et} and A_{Lt} represent the bias of technological change, here assumed not sector-specific. The assumption on whether A_{Et} and A_{Lt} are endogenous or exogenous is important for model's predictions. The TFP term Φ_{jt} is assumed exogenous and sector-specific. About the production structure, sectors differ with respect to their energy share, so that $\nu_m > \nu_s$, but they have the same elasticity of substitution $\sigma_m = \sigma_s = \sigma$ (in line with empirical evidence, see Baccianti 2013).

The aggregate energy intensity θ_t is a weighted average of sectoral energy intensities:

$$\theta_t = \frac{E_t}{Y_t} = \theta_{mt}\left(\omega_{mt}/\frac{p_{mt}}{p_t}\right) + \theta_{st}\left(\omega_{st}/\frac{p_{st}}{p_t}\right)$$

where $\theta_{jt} = {}^{E_{jt}}/_{Y_{jt}}$, $j \in \{m, s\}$, is the sectoral energy intensity and ω_{st} is the value added share of the service sector. A closer look at these two terms reveals that they are both functions of the underlying processes of biased and unbiased technological change, together with factor prices. Given the production possibility frontier (5), the optimal energy intensity in each sector j is

$$\theta_{jt} = \frac{E_j}{Y_{jt}} = \frac{1}{A_{Et}\Phi_{jt}}\nu_j^{\sigma}\left[\nu_j^{\sigma} + (1-\nu_j)^{\sigma}\left(\frac{A_{Et}}{A_{Lt}}\frac{w_t}{p_{Et}}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}. \tag{6}$$

The rise in the relative energy price reduces the sectoral energy intensity because of factor substitution. The sectoral energy intensity is not only the result of the level of technical dependence of production to energy, ν_j, but also the level of technological efficiency due to factor-specific technology A_{Et} and the more general level of production efficiency in sector j, that is the TFP term Φ_{jt}. The efficiency coefficient of energy $(A_{Et}\Phi_{jt})$ - including biased and unbiased technological change - also lowers the amount of energy demand for unit of output. The change in sectoral energy intensity has the following specification:

$$\hat{\theta}_{jt} = -\hat{\Phi}_{jt} - \hat{A}_{Et} + \sigma(1-\kappa_{jt})(\hat{A}_{Et} - \hat{A}_{Lt}) + \sigma(1-\theta_{Ejt})(\hat{w}_t - \hat{p}_{Et}), \tag{7}$$

where $\kappa_{jt} = \left[1 + \left(\frac{1-\nu_j}{\nu_j}\right)^{\sigma}\left(\frac{A_{Lt}}{A_{Et}}\frac{p_E}{w}\right)^{\sigma-1}\right]^{-1}$. Clearly, the impact of biased technological change and relative input price changes depend on sectoral factor shares.

Induced Factor-biased Technological Change At this point it is necessary to endogenise the bias of technological change, using a functional form that is suitable for a numerical exercise. Following the literature of directed technological change (e.g. Acemoglu 2002, Smulders and de Nooij 2003), the change in relative factor efficiency is a function of the input price ratio and of the elasticity of substitution σ. As research incentives follow input cost shares, the increase in the relative price of energy redirects research effort towards energy in the case inputs are complements. Research is redirected to labour instead if inputs are substitutes. The change in relative factor efficiency is then governed by the following function:

$$\hat{A}_{Et} - \hat{A}_{Lt} = a_t + \vartheta\left(\sigma - 1\right)\left(\hat{w}_t - \hat{p}_{Et}\right), \tag{8}$$

where a_t is an autonomous component of directed technological change, for instance the effect of governmental research programs, and $0 < \vartheta < 1$. Relationship (8) is only limited to define the change relative factor efficiency, not the change in absolute levels (i.e. $\hat{A}_{Et}$). Assume for the moment that $a_t = 0$, equation (7) becomes

$$\hat{\theta}_{jt} = -\hat{\Phi}_{jt} - \hat{A}_{Et} + \sigma(1-\theta_{Ejt})\left(1+\vartheta\left(\sigma-1\right)\right)\left(\hat{w}_t - \hat{p}_{Et}\right). \tag{9}$$

Aggregate Energy Intensity, Technique and Composition Effects The change in aggregate energy intensity is now rewritten as a function of relative input price changes and technological progress. Details are shown in Appendix 1.

$$\hat{\theta}_t = -\frac{1}{\theta_t}\left[\theta_{mt}(1-\omega_{st})\hat{\Phi}_{mt} + \theta_{st}\omega_{st}\hat{\Phi}_{st}\right] + \left[(1-\epsilon_{st})\chi_{mt} - \epsilon_{st}\chi_{st}\right]\mu\left(\hat{\Phi}_{st} - \hat{\Phi}_{mt}\right) - \hat{A}_{Et} +$$

$$+\frac{\omega_{st}}{\theta_t}\left[\theta_{st} - \theta_{mt}\right]\hat{\omega}_{st} +$$

$$+\left\{\left[(1-\epsilon_{st})\chi_{mt} - \epsilon_{st}\chi_{st}\right]\left(\kappa_{st} - \kappa_{mt}\right) + \sigma\left[(1-\kappa_{mt})(1-\epsilon_{st}) + (1-\kappa_{st})\epsilon_{st}\right]\right\}\xi(\hat{w}_t - \hat{p}_{Et}). \tag{10}$$

where $\chi_{mt} = \frac{(1-\pi)^{\varepsilon}\left(\frac{p_{st}}{p_{mt}}\right)^{1-\varepsilon}}{\pi^{\varepsilon}+(1-\pi)^{\varepsilon}\left(\frac{p_{st}}{p_{mt}}\right)^{1-\varepsilon}}$, $\chi_{st} = \frac{\pi^{\varepsilon}\left(\frac{p_{mt}}{p_{st}}\right)^{1-\varepsilon}}{\pi^{\varepsilon}\left(\frac{p_{mt}}{p_{st}}\right)^{1-\varepsilon}+(1-\pi)^{\varepsilon}}$ and $\xi = (1+\vartheta\left(\sigma-1\right))$. Moreover, $\epsilon_{st} = \frac{E_{st}}{E_t}$ is the sectoral share in total energy use. The theory developed so far has essential and quite basic features, nevertheless it has all elements for a complete analysis of energy intensity. Both the effects of technology variables and relative prices can be interpreted in terms of the composition and technique effects. The first line of equation (10) shows how sectoral TFP growth affects aggregate energy intensity, in particular the role of sectoral technology differences. On the unbiased side of the technique effect, the aggregate impact of sectoral TFP growth is weighted over the sector's share of total energy consumption. Notice that over time the reallocation of value added towards services increases the weight of $\hat{\Phi}_{st}$ and tends to reduce aggregate TFP growth (I will get back to this point at the end of the paper). A straightforward implication of equation (10) is that technology is more effective on aggregate energy intensity if it has an economy-wide impact, having a one-to-one effect on $\hat{\theta}_t$. On the biased side of the technique effect - expressed as a function of input prices in equation (10) - labour-biased technological change tends to reduce aggregate intensity in addition to the pure improvement in energy efficiency. That increases with the labour share, because the induced increase in production is higher than any possible complementarity effect on energy demand.

About the composition effect, changes in the value added share of the service sector might have a positive or negative impact on aggregate intensity depending on whether the service sector is more energy intensive than the industrial sector or not. As data show $\theta_{st} < \theta_{mt}$, higher value added growth in the service sector pulls down aggregate energy intensity. The size of this effect is $|\frac{\omega_{st}}{\theta_t}[\theta_{st} - \theta_{mt}]|$, which might be above unity and greater than the TFP growth effect. The third component is the classic price effect. Differently from a one-sector model, in this case the effect is a weighted average of sectoral factor shares in energy use. Input substitution is often ignored in the interpretation of the technique effect, but it is a major determinant and cannot be considered as technological progress.

The composition and technique effects are also strongly interdependent because are both functions of relative input prices and productivity changes. The relative change in services' value added share in equation (10) is endogenous and dependent on relative TFP growth as well as factor price changes. The equation for the induced variation in the value added share of the service sector can be obtained differentiating (4) and using (8) and the expression for changes in real sectoral output prices (see Appendix),

$$\hat{\omega}_s = \lambda_{st}\frac{1-\varepsilon}{(1-\psi_{st})}(\theta_{Est} - \theta_{Emt})\xi\left(\hat{p}_E - \hat{w}\right) - \lambda_{st}\frac{1-\varepsilon}{(1-\psi_{st})}\mu\left(\hat{\Phi}_{st} - \hat{\Phi}_{mt}\right) - \lambda_{st}\hat{y}_t,$$

where $\lambda_{st} = \frac{(1-\omega_{st})(1-\psi_{st})}{1+(1-\omega_{st})(1-\psi_{st})}$, $\psi_s = \frac{y_s}{y_s+\bar{y}_s} \leq 1$ and $\hat{y}_t$ is the change in aggregate output. At the moment factor markets are not modelled and relative input prices are treated as exogenous, an indirect way to control for policies affecting the price of energy and labour in the short time frame I am going to consider in the next section.

Therefore, the composition effect is a function of input prices and technological progress as well as the technique effect. This fact creates a crucial interdependence between these effects, rarely accounted for in decomposition analysis studies.

3 Theory and Data Trends

Even the simplest theoretical framework is more advisable than decomposition analysis to identify the foundamental drivers of energy intensity dynamics. The next step is to present a set of stylized fact for a group of developed countries and evaluate to which extent theory is able to explain those data trends. Table 1 presents average growth rates for energy intensity, TFP and relative energy price (with respect to wages) for a group of European countries. Energy intensity data are obtained from the Odyssee project's database (Odyssee Project 2013) and are highly harmonized, defined as koe per value added at 2005 euro PPP prices. For TFP, Table 1 reports geometric averages of annual multifactor productivity growth obtained from the OECD Productivity Statistics database. Changes in energy prices relative to wages are calculated using data from the WIOD database (Timmer 2012)

	EI (2000-2011)				TFP (2000-2009)			Pe/W (1995-2008)
	$\hat{\theta}$	$\hat{\theta}_m$	$\hat{\theta}_s$	$\hat{\theta}_s - \hat{\theta}_m$	$\hat{\Phi}_m$	$\hat{\Phi}_s$	$\hat{\Phi}_{mt} - \hat{\Phi}_{st}$	$\hat{p}_{Et} - \hat{w}$
Austria	-0.48	.15	-.73	*-.88*	2.15	.62	1.54	.82
Belgium	-0.90	-1.68	0.26	*1.94*	1.47	-.81	2.28	1.40
Czech Republic	-3.23	-6.36	-2.44	*3.91*	5.76	4.00	1.76	-4.81
Denmark	-0.84	-0.49	-0.93	*-.44*	2.08	1.74	0.34	1.93
Finland	-1.69	-2.67	0.61	*3.28*	4.03	0.52	3.51	.40
France	-1.30	-1.94	-0.62	*1.32*	3.00	0.90	2.11	1.92
Germany	-1.56	-0.49	-2.41	*-1.92*	0.92	0.79	.12	1.38
Greece	-3.40	-3.79	-1.04	*2.75*	1.48	2.90	-1.42	0.31
Ireland	-5.82	-5.61	-8.00	*-2.39*	4.62	(*)	(*)	1.07
Italy	-0.40	-1.95	2.21	*4.16*	0.34	-.52	.86	4.42
Netherlands	-1.35	-2.23	-0.38	*1.85*	2.92	1.98	.94	2.09
Poland	-2.56	-5.94	0.71	*6.65*	5.28	0.67	4.61	2.24
Spain	-1.00	-1.54	0.76	*2.30*	-.031	-.086	.055	1.30
Sweden	-4.05	-3.18	-2.08	*1.10*	2.51	1.00	1.51	2.60
United Kingdom	-3.28	-8.70	-9.74	*-1.04*	3.54	3.70	-.17	1.41

Table 1: Energy intensity, TFP and relative energy prices, average annual percentage change, 1995-2008.

Note: aggregate data in the first column are not averages of manufacturing and services values, because including also the agricultural and residential sector. (*) data not available.

and the IEA Energy Prices and Taxes database, as described in Baccianti (2013).

Input prices are assumed exogenous because several energy policies have been implemented in European countries during this period and also because for most fuels the price is set in international markets, not modeled here. From 1995 to 2008, the relative price of energy rose in all countries except Czech Republic. Yearly 1-2 % increases in the price of energy with respect to wages over 15 years implies a substantial shift in relative input prices. As a first order effect, firms are induced to substitute out energy with alternative inputs and reduce the energy intensity. Equation (10) shows how rising energy prices pull down the aggregate energy intensity through reduction in sectoral intensities. In all countries except Spain and Belgium, the manufacturing and service sectors had positive annual growth rates in TFP, indicating advances in productivity that should have as well boosted energy efficiency.

A qualitative analysis of the aggregate trends reported in Table 1, data patterns appear in line with equation (10). High average TFP growth and high increase in the relative energy price

Sectoral Differences in Energy Intensity Changes One interesting feature of the data is the presence of systematic differences in energy intensity changes between the manufacturing and the service sectors. The convergent or divergent dynamics of the sectoral intensity gap is crucial for the intensity of the composition effect over time. The sign of the growth difference, shown in Table 1, is positive in some countries and negative in others. The model presented in the previous section is able to address this point and to suggest factors that might generate such an uneven pattern. Back to equation (9), heterogeneity in factor cost shares and TFP growth across sectors are responsible for potential differences in energy intensity changes, as follows:

$$\hat{\theta}_{st} - \hat{\theta}_{mt} = \hat{\Phi}_{mt} - \hat{\Phi}_{st} + \sigma\left(\kappa_{mt} - \kappa_{st}\right)\left(\hat{A}_{Et} + \hat{w}_t - \hat{p}_{Et} - \hat{A}_{Lt}\right). \tag{11}$$

Evidence from Table 1 suggests that TFP growth in the manufacturing sector tends to be higher than in services. Together with productivity growth, changes in relative input prices in efficiency units are as well responsible for uneven patterns in energy intensities because of heterogeneity in energy cost shares. Notice that if $\kappa_{mt} = \kappa_{st}$, differences in energy intensity between the industrial and service sector are only attributable to TFP growth rates, but this case is not empirically relevant. Given that $\kappa_{mt} > \kappa_{st}$, we expect the relative energy intensity change as defined in equation (11) to be negative only if the relative increase in the cost of energy in efficiency units is particularly strong. This result is due to the nonlinearity of the production function. For a single sector - equation (9) - the sensitivity of energy intensity to input price changes decreases with the level of energy intensity, therefore an increase in the relative energy price induces a smaller adjustment in the energy intensity of the manufacturing sector compared to the service sector.

Using equation (8) the previous equation can be rewritten to account for endogenous price-induced biased technological change:

$$\hat{\theta}_{st} - \hat{\theta}_{mt} = \hat{\Phi}_{mt} - \hat{\Phi}_{st} + \xi\sigma\left(\kappa_{mt} - \kappa_{st}\right)\left(\hat{w}_t - \hat{p}_{Et}\right), \tag{12}$$

where $\xi = \vartheta\left(\sigma - 1\right) + 1 > 0$. This equation is now a function of input price changes alone, and efficiency units are endogenously determined without introducing qualitative variations to the relationship described in equation (11).

Input Price Changes Back to the data, does a correlation between these variables exists? Holding TFP constant and using data for relative price changes between 2000 and 2009, I find no statistically significant correlation for the group of European countries (Figure 1). In the rather short time period considered so far, input prices appear not to play a relevant role in generating sectoral

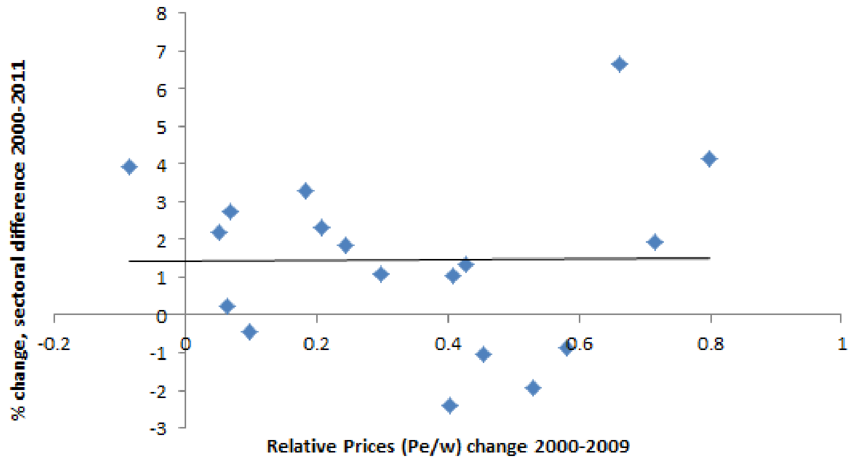

Figure 1: Growth in service-industry energy intensity gap and relative energy prices. Sources: WIOD, Odyssee, IEA-OECD

differences in energy intensity changes. In the long run, a well known fact is the relative increase of wages with respect to energy prices, the opposite of what happened in the year 2000s. According to equation (12) and leaving aside TFP growth, in the long run we should observe $\hat{\theta}_{st} > \hat{\theta}_{mt}$ a faster decrease in the energy intensity of the manufacturing sector compared to services. I collect additional data from the EU-KLEMS dataset to calculate sectoral energy intensity trends between 1980 and 2005 and find that in most but not all countries the energy intensity decline is faster in manufacturing.

Extension 1 - Endogenous sectoral TFP growth The basic model has exogenous sectoral TFP growth. The theory of endogenous technological change (i.e. Romer 1990 and for energy, Bretschger and Pittel 2010) suggests that sectoral productivities are driven by research incentives following input prices. According to Bretschger and Pittel (2010), an increasing energy scarcity due to environmental policy leads to a steady state in which research is directed towards the manufacturing sector because it is the most energy intensive. Such models predict a positive relationship between TFP growth and energy prices that is stronger the highest is the sectoral energy intensity. Over the period 2000-2011 a widespread increase in energy prices occurs together with a faster TFP growth in manufacturing. This theory predicts $\hat{\theta}_{st} > \hat{\theta}_{mt}$, the opposite with respect to the the basic model, which does not hold for all countries.

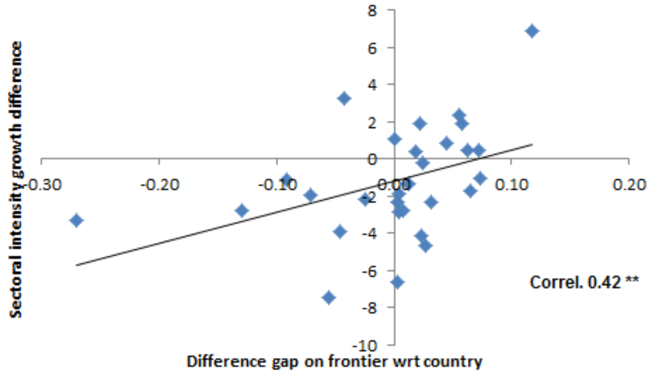

Figure 2: Relationship between Δ_{it} and $\hat{\theta}_{m,it} - \hat{\theta}_{s,it}$ (2000-2011)

Extension 2 - Distance to Sector-specific Frontier One potential direction to improve the model's data fitting is to integrate a sector-specific distance to frontier mechanism. Countries that experienced a stronger reduction of energy intensity in the service sector might have been lagging behind with respect to energy efficient technology in that sector compared to the technology frontier, but not in manufacturing. Define $\bar{\theta}_{jt}$ the technological frontier of sector j at time t . Most countries are likely not to lie on the efficiency frontier but rather to lag behind in terms of the adopted technology. I define $\bar{\theta}_{jt} - \theta_{jt,i}$ the measure of the distance of country i's sector from the international frontier at time t. The larger is $\bar{\theta}_{jt} - \theta_{jt,i}$, the faster is the reduction in energy intensity in sector j. Therefore, the change in the sectoral intensity gap depends on the Δ_{it}, the deviation of the intensity gap in the country with respect to the frontier:

$$\Delta_{it} = \underbrace{(\bar{\theta}_m - \bar{\theta}_s)}_{\text{Sectoral gap on frontier}} - \underbrace{(\theta_{m,it} - \theta_{s,it})}_{\text{Sectoral gap in the country}} \stackrel{+}{\rightarrow} \hat{\theta}_{m,it} - \hat{\theta}_{s,it}.$$

A country experiences a reduction in the sectoral intensity gap if the current sectoral gap is larger than in the frontier. Using the Odyssee data of Section 2, I calculate the correlation between the change in energy intensity for each sector and the deviation with respect to the average sectoral intensity gap across countries. The correlation is statistically significant at 5% and confirms the importance of the distance to frontier to explain sectoral intensity gaps.

4 Achilles or the Tortoise? A Numerical Exercise

The previous analysis has highlighted the importance of sectoral heterogeneity in energy intensities and TFP growth for aggregate energy productivity trends. On the one hand, aggregate energy intensity is reduced following the static effect of a shift from manufacturing production to services, because the latter is a less energy consuming economic activity. On the other hand, the service sector is characterized by a lower productivity growth and the shifting resources to services has the dynamic effect to lower the contribution of productivity growth to reducing aggregate energy intensity. From a policy perspective, a question arises: is the shift to a service-based economy leading to the lowest possible energy intensity in the long-run? Shall we rely on the fast Achilles (manufacturing) or the slow but better positioned Tortoise (services)? The former might never reach the latter in terms of energy intensity.

In order to answer this question I carry out a numerical exercise based on the model used so far in this paper. The model has a slim structure and parameters can be quite straightforwardly calibrated. For this preliminary numerical exploration of the model I calibrate it to German data. The list of parameter values is shown in Table 2. The elasticity of substitution in the utility function, ε, is set to a very low value following the results of Herrendorf et al. (2013b) for US data. This paper provides additional information to calibrate the utility function, as for the π and the non-homotheticity constant $\bar{y}_s$(since in my model quantities are normalized, the latter is derived as the fraction of the constant estimated by Herrendorf et al. over the service sector value added in 2000). On the production side, average TFP growth rates and factor shares ν_j (cost shares) are obtained from the EU-KLEMS database (Timmer and O'Mahony 2009).

Relative input prices are taken as exogenous processes. From WIOD and OECD data I find an annual 6 percent average increase in the relative energy price over 2000-2011. The pricing process (Figure 2b) is assumed non-linear and represented by the following function:

$$\hat{p}_{Et} - \hat{w}_t = 0.4\frac{e^{-(0.4t-2)}}{\left(1+e^{-(0.4t-2)}\right)^2} - 0.01, \tag{13}$$

The previous function is split into two components. A first term is a logistic function of time and it generates an average annual rate of change in the relative input price of 5.76 percent in the first 12 periods of the simulation. The second linear component instead represents the stylized fact about input prices: wages increase more than energy prices in the long run. The economy is assumed to grow at a constant annual rate of 2 percent and the value added share of the service sector ω_{s0} for the base year is calibrated to year 2000. Sectoral energy intensities for the base year, θ_{m0} and

σ	.5	g	.02
ε	.1	$\bar{y}_s$	.075
ν_m	.096	ν_s	.018
$\hat{\Phi}_m$	.025	$\hat{\Phi}_s$	.002
π	.18	ω_{s0}	.7
θ_{m0}	.107	θ_{s0}	.025
ϑ	.2	μ	1

Table 2: Parameter Calibration

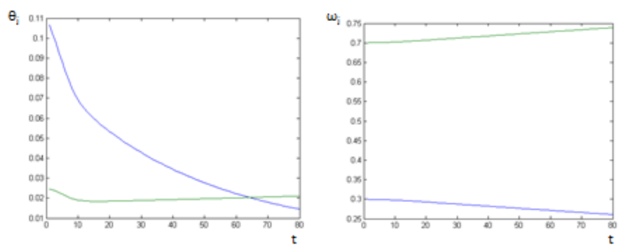

Figure 3: Simulation Results - Energy intensity (left panel) and sectoral value added shares (right panel) for industry (green) and services (blue).

θ_{s0}, are obtained from the Odyssee database and are used to calibrate the sectoral energy efficiency levels ($A_{E0}\Phi_{m0} = 14.91$ and $A_{E0}\Phi_{s0} = 49.81$). The value ϑ is set with a value that gives an annual rate of relative efficiency growth, given the price dynamics, of no more than 1 percent annually .

4.1 Simulation Results

First, I simulate the model for $T = 80$ periods to get a flavour of the model's long run properties. Figure 2 shows the structural transformation experienced by the economy (right panel) and the trends in sectoral energy intensities. The value added share of the service sector slowly expands and the manufacturing sector shrinks, mostly because of the income effect and differences in TFP growth. Energy intensity in the manufacturing sector exhibits a sharp reduction over time, whereas the service sector keeps a constant use of energy per unit of value added with an initial temporary decline. The composition effect and the energy intensity improvements in the manufacturing sector are mostly responsible for the decline in aggregate energy intensity in Figure 3a. Figure 2a shows that in the very long run the manufacturing sector overcomes the service sector in terms of energy intensity.

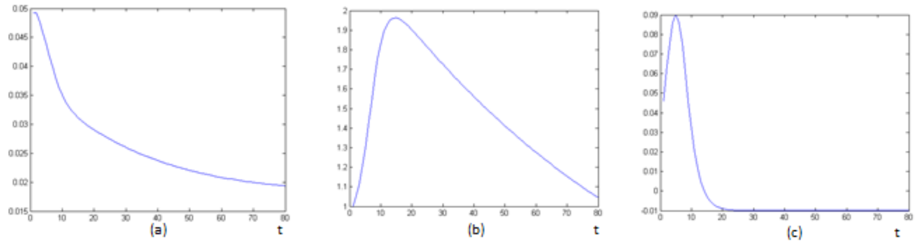

Figure 4: Simulation Results - Aggregate energy intensity (a), relative energy price (b) and variation in relative energy efficiency (c).

5 Final Remarks and Next Steps

In this paper I discuss how a simple theoretical model of aggregate and sectoral energy intensity is able to replicate existing data facts, for instance the dynamics of sectoral intensity gap and patterns in relative input prices. A theoretical framework is a necessary complement to the results obtained from the decomposition analysis literature. In fact, the composition (structure) and technique (intensity) effects are deeply interdependent and contain an important driver, the substitution effect, that represent neither a structural nor a innovation effect.

After showing the limits of the basic model with exogenous sectoral TFP in matching data facts, I discuss two potential model extensions. The endogenous technological change theory with endogenous TFP growth driven by factor prices does not perform well. In the long run, increasing relative wages observed in the data is not compatible with the persistent higher TFP growth rate in the manufacturing sector, according to the theory. In both long and short rum, the endogenous TFP model predicts faster energy intensity reduction in the manufacturing sector, which is not observed in all countries. The convergence theory or sectoral distance to frontier theory has more solid empirical foundations. However, the technological catching-up effects have to be carefully separated from the income effects leading to structural transformation in favour of less energy intensive production activities.

Finally, the theoretical framework is used to analyse if a shift in final demand towards services is the best scenario for reducing aggregate energy intensity in the long-run. The current version of the paper shows some preliminary simulation results for Germany. Results show a beneficial level effect for energy demand in the medium-run (services have lower energy shares), but in the longer term the manufacturing sector could potentially overcome the service sector in energy efficiency. However, even if this outcome stays robust to further model and data extensions, the transition path should as well be analysed and take into account the medium-run benefits of a quick shift to a service-based economy.

This paper presents preliminary results. The next steps involve the dataset extension to a longer time period and to a broader set of countries, possibly to the whole OECD group.

References

[Acemoglu(2002)] Acemoglu, Daron. 2002. "Directed Technical Change." *Review of Economic Studies* 69 (4):781–809. URL http://EconPapers.repec.org/RePEc:bla:restud:v:69:y:2002:i:4:p:781-809.

[Ang and Zhang(2000)] Ang, Beng Wah and FQ Zhang. 2000. "A survey of index decomposition analysis in energy and environmental studies." *Energy* 25 (12):1149–1176.

[Ang(2004)] Ang, BW. 2004. "Decomposition analysis for policymaking in energy: which is the preferred method?" *Energy policy* 32 (9):1131–1139.

[Arseneau(2011)] Arseneau, David. 2011. "Explaining the energy consumption portfolio in a cross-section of countries: are the BRICs different?" *FRB International Finance Discussion Paper* (1015).

[Baccianti(2013)] Baccianti, Claudio. 2013. "Estimation of Sectoral Elasticities of Substitution along the International Technology Frontier." *ZEW Discussion Papers* .

[Brock and Taylor(2005)] Brock, William A. and M. Scott Taylor. 2005. "Chapter 28 Economic Growth and the Environment: A Review of Theory and Empirics." Elsevier, 1749 – 1821. URL http://www.sciencedirect.com/science/article/pii/S1574068405010282.

[Grossman and Krueger(1995)] Grossman, Gene M and Alan B Krueger. 1995. "Economic growth and the environment." *The quarterly journal of economics* 110 (2):353–377.

[Herrendorf, Herrington, and Valentinyi(2013)] Herrendorf, Berthold, Christopher Herrington, and Akos Valentinyi. 2013. "Sectoral Technology and Structural Transformation." CEPR Discussion Papers 9386, C.E.P.R. Discussion Papers. URL http://ideas.repec.org/p/cpr/ceprdp/9386.html.

[Herrendorf, Rogerson, and Valentinyi(2013)] Herrendorf, Berthold, Richard Rogerson, and Akos Valentinyi. 2013. "Two Perspectives on Preferences and Structural Transformation." *American Economic Review* 103 (7):2752–89. URL `http://www.aeaweb.org/articles.php?doi=10.1257/aer.103.7.2752`.

[IEA(2008)] IEA. 2008. "Worldwide Trends in Energy Use and Efficiency." .

[IEA(2013b)] ———. 2013b. "Energy Efficiency Market Report 2013." .

[Jorgenson and Timmer(2011)] Jorgenson, Dale W. and Marcel P. Timmer. 2011. "Structural Change in Advanced Nations: A New Set of Stylised Facts." *Scandinavian Journal of Economics* 113 (1):1–29.

[Klenow(1998)] Klenow, Peter J. 1998. "Ideas versus rival human capital: Industry evidence on growth models." *Journal of Monetary Economics* 42 (1):3–23.

[Kuznets and Murphy(1966)] Kuznets, Simon and John Thomas Murphy. 1966. *Modern economic growth: Rate, structure, and spread*. Yale University Press New Haven.

[Ma(2014)] Ma, Chunbo. 2014. "A multi-fuel, multi-sector and multi-region approach to index decomposition: An application to China's energy consumption 1995–2010." *Energy Economics* 42:9–16.

[O'Mahony and Timmer(2009)] O'Mahony, Mary and Marcel P Timmer. 2009. "Output, input and productivity measures at the industry level: The eu klems database*." *The Economic Journal* 119 (538):F374–F403.

[Pittel and Bretschger(2010)] Pittel, Karen and Lucas Bretschger. 2010. "The implications of heterogeneous resource intensities on technical change and growth." *Canadian Journal of Economics* 43 (4):1173–1197.

[Project(2013)] Project, ODYSSEE. 2013. "ODYSSEE-Database." Database developed by enerdata, grenoble under the energy efficiency indicator eu/save-project co-ordinated by ademe, paris, technical co-ordination enerdata, grenoble and fhg-isi, karlsruhe.

[Romer(1990)] Romer, Paul Michael. 1990. "Endogenous Technological Change." *Journal of Political Economy* 98 (5):S71–102.

[Rostow(1990)] Rostow, Walt Whitman. 1990. *The stages of economic growth: A non-communist manifesto*. Cambridge University Press.

[Smulders and de Nooij(2003)] Smulders, Sjak and Michiel de Nooij. 2003. "The impact of energy conservation on technology and economic growth." *Resource and Energy Economics* 25 (1):59–79.

[Timmer(2012)] Timmer, M.P. 2012. "The World Input-Output Database (WIOD): Contents, Sources and Methods." *available at http://www.wiod.org/database/index.htm* .

1. Calculation of Aggregate Energy Intensity

At the aggregate level, the change in aggregate energy intensity is driven by changes in sectoral intensities and value added shares:

$$\hat{\theta}_t = (1-\epsilon_{st})\left[\hat{\theta}_{mt} - \hat{\omega}_{st}\frac{\omega_{st}}{(1-\omega_{st})} - (\hat{p}_{mt} - \hat{p}_t)\right] + \epsilon_{st}\left[\hat{\theta}_{st} + \hat{\omega}_{st} - (\hat{p}_{st} - \hat{p}_t)\right], \tag{14}$$

with $\epsilon_{st} = \frac{E_{st}}{E_t} = \theta_{st}\omega_{st}\frac{1}{\theta_t}$. Plug (7) into (14) and get

$$\hat{\theta}_t = -\frac{1}{\theta_t}\left[\theta_{mt}(1-\omega_{st})\hat{\Phi}_{mt} + \theta_{st}\omega_{st}\hat{\Phi}_{st}\right] + \frac{\omega_{st}}{\theta_t}\left[\theta_{st} - \theta_{mt}\right]\hat{\omega}_{st} +$$

$$-(1-\epsilon_{st})(\hat{p}_{mt} - \hat{p}_t) - \epsilon_{st}(\hat{p}_{st} - \hat{p}_t) +$$

$$-\hat{A}_{Et} + (1 + \vartheta(\sigma - 1))\sigma\left[(1-\theta_{Emt})(1-\epsilon_{st}) + (1-\theta_{Est})\epsilon_{st}\right](\hat{w}_t - \hat{p}_{Et}) \tag{15}$$

The rate of change of the real output price in sector j is

$$\hat{p}_{jt} - \hat{p}_t = \chi_{jt}(\theta_{Es} - \theta_{Em})(1 + \vartheta(\sigma - 1))(\hat{p}_{Et} - \hat{w}_t) - \chi_{jt}\mu\left(\hat{\Phi}_{st} - \hat{\Phi}_{mt}\right), \tag{16}$$

where

$$\chi_{mt} = \frac{(1-\pi)^{\varepsilon}\left(\frac{p_{st}}{p_{mt}}\right)^{1-\varepsilon}}{\pi^{\varepsilon} + (1-\pi)^{\varepsilon}\left(\frac{p_{st}}{p_{mt}}\right)^{1-\varepsilon}}, \quad \chi_{st} = \frac{\pi^{\varepsilon}\left(\frac{p_{mt}}{p_{st}}\right)^{1-\varepsilon}}{\pi^{\varepsilon}\left(\frac{p_{mt}}{p_{st}}\right)^{1-\varepsilon} + (1-\pi)^{\varepsilon}},$$

and μ is the parameter of the profit margin $M_{jt} = \left(\frac{1}{\Phi_j}\right)^{\mu}$ for $p_{jt} = M_{jt}UC_{jt}$, where UC_{jt} are unitary costs (as in Klenow 1998). Call $\xi = (1 + \vartheta\,(\sigma - 1))$, equation (15) becomes equation (10) in the text.