Labour productivity growth and energy in Europe: a production-frontier approach*

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Abstract

Energy use has gained increasing attention when assessing economic growth and convergence of countries. Indeed, recent policy and regulatory implementations require a reduction of non-renewable energy use (to decrease greenhouse gas emissions) and a rise in renewable energy use. As such, many studies have tried to understand the contribution of energy on growth and convergence. In this paper, we propose to use a production-frontier approach to tackle this question. The distinguishing features of our methodology are: no assumptions about the growth process are required, and it isolates the impact of non-renewable and renewable energy. We apply our methodology to the case of the European countries from 1995 to 2015. We find that renewable energy changes cause a divergence, while non-renewable energy changes cause a convergence. We also find that the impact of both types of energy on economic growth, while small, is not negligible and increases with time. Next, we identify two groups: Eastern and central Europe and EU12, and show that the impact of both types of energy is different for each group. Finally, we relate our findings to several variables. This last part reveals important patterns and policy implications.

Keywords: growth; convergence; production-frontier; energy; Europe.

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1 Introduction

Typically, two main approaches are used to study economic growth and convergence of countries. This first approach, initiated by Solow (1956), decomposes economic growth into different components to determine its sources. The second approach, initiated by Baumol (1986) and Barro (1991), uses econometric tools to determine if there is a tendency for the world's economies to converge over time. Two main criticisms of these approaches have been addressed. One, they are heavily model driven; they rely on particular assumptions about the technology, market structure, technological change, market imperfections or other aspects of the growth process. In practice, these assumptions are typically unverifiable and clearly have huge impacts on the results. It could, in the worst case, bias the results. Two, Quah (1993, 1996, 1997) and others (e.g. Galor (1996), Jones (1997), Johnson (2005), and Henderson, Parmeter and Russell (2008)) argued that these model-driven methods are not appropriate since they do not capture the bi-modality of the labour productivity distribution, i.e. they ignore the division of the world into two groups: rich and poor. These two drawbacks could explain why empirical growth studies based on model driven approaches have led to different results.

Kumar and Russell (2002) have proposed a production-frontier method to address the two issues. Instead of imposing assumptions on the growth process, their production-frontier method reconstructs the world production frontier using only the available data (i.e. a nonparametric reconstruction). Attractively, in line with the initial work of Solow (1956), their production-frontier method decomposes labour productivity growth into three parts - three indexes: (1) technological change, i.e. shifts in the world production frontier, (2) technological catch-up, i.e. movements toward or away from the frontier, and (3) physical capital change, i.e. movements along the frontier. Also, in line with Baumol (1986) and Barro (1991), the decomposition is used to better understand the cause of the convergence/divergence between countries. Building on the endogenous growth models of Lucas (1988) and Romer (1990), Henderson and Russell (2005) extended the work of Kumar and Russell (2002) by incorporating human capital.

While production-frontier approaches have clearly revealed their usefulness in practice, a major drawback is the absence of energy in their modelling.[1] Recently,

[1]See, for example, Färe, Grosskopf and Margaritis (2006, 2007), Badunenko, Henderson and

integrating energy use in economic growth models has gained interest in the literature. Two main reasons explain this particular attention. One, energy use is a pre-condition for economic activity and generating growth, and could place strong constraints on economic activity in the case of scarcity. Therefore, neglecting this production factor in the model would imply ignoring the impacts and constraints on economic growth and thus bias the analysis. Two, energy use is present in all major policy and regulatory implementations (such as the Kyoto Protocol, the Europe 2020 and 2030 strategy, the Paris Agreement). In particular, there is an increased campaign to reduce non-renewable energy and increase renewable energy, associated with a decrease of the greenhouse gas emissions (the undesirable side-products of economic growth). Consequently, many countries have increased their investment in renewable energy production and decreased their non-renewable energy use. Therefore, neglecting energy use also means ignoring these major policy and regulatory implementations and their impact on economic activity (via, for example, a change in the country investment behaviours). In conclusion, it is a major aspect of economic growth that is forgotten when not taking energy use into account.

In this paper, we extend the works of Kumar and Russell (2002) and Henderson and Russell (2005) by incorporating energy use as an extra production factor. As such, we keep the same features as their initial works, i.e. no assumption on any aspect of the growth process and a decomposition of the labour productivity into different sources, with the extra advantage of taking energy use into account. We make an explicit distinction between renewable and non-renewable energy. Indeed, as discussed before, these two types of energy have different features, and could potentially have different impacts on economic growth and convergence. We end up with a decomposition of labour productivity into six parts - six indexes. The three parts/indexes present in Kumar and Russell (2002): (1) technological change, (2) technological catch-up, and (3) physical capital change; the fourth part/index added by Henderson and Russell (2005): (4) human capital change; and two extra components/indexes, one for each type of energy: (5) renewable energy change, and (6) non-renewable energy change.

We apply our method to the case of 26 European countries during the period

Zelenyuk (2008), and Badunenko, Henderson and Russell (2013) for applications for countries; Enflo and Hjertstrand (2009), Badunenko and Tochkov (2010), and Badunenko and Romero-Avila (2014) for applications for regions; and Walheer (2016a, b, 2018a, c) for applications for sectors.

1995-2015. We find that renewable energy and non-renewable energy changes have small but non-negligible opposite effects on economic growth. Moreover, the impacts of energy changes on economic growth implode over time, probably due to the recent policy and regulatory implementations; and changes in energy use, as a whole, induce a divergence between the European countries. Next, we identify two groups within the European countries: Eastern and central Europe and EU12, and show that the impact on the economic growth of both types of energy is clearly different for each group. Finally, we relate our findings to several variables and recent policy implementations. This last part reveals important patterns and policy implications.

The rest of the paper is structured as follows. In Section 2, we define the technology and show how to decompose labour productivity into six components. In Section 3, we present the results. In Section 4, we conclude.

2 Literature review

We present a literature review of the energy and economic growth nexus. This allows us to better motivate and position the use of the production-frontier approach in that context, and, in particular, to highlight what the production-frontier approach brings to the debate. Given our research question, we focus our discussion on three aspects of the energy and economic growth nexus: the relationship between energy and economic growth; the distinction between renewable and non-renewable energy; and energy as a necessary condition to economic growth.

Our review highlights four important facts: (1) there is no clear relationship between energy and economic growth, even when relying on advanced (parametric) econometric tools; (2) renewable and non-renewable energy have different impacts on economic growth; (3) capital and labour should be present in the analysis to avoid bias of omitted variables; and (4) energy plays a role as a production factor for economic output. These four facts form our prime motivation to use the production-frontier approach to tackle the energy and economic growth nexus.

2.1 Energy and economic growth relationship

Usually, four different relationships are tested between energy quantity and economic growth: (1) the growth hypothesis, i.e. a unidirectional relationship from energy to economic growth; (2) the feedback hypothesis, i.e. a bidirectional relationship; (3) the neutrality hypothesis, i.e. no causality relationship; and (4) the conservation hypothesis, i.e. a relationship from economic growth to energy. The number of empirical works for each of the four hypotheses is abundant. Nevertheless, no consensus is found in the literature. This is rather clear when looking at recent literature reviews. Indeed, while the reviews of Ozturk (2010), Payne (2010), Chen, Chen and Chen (2012), Kalimeris, Richardson and Bithas (2014), Menegaki (2014), Omri (2014), and Tiba and Omri (2017) are based on different methods and include different numbers of studies, they all endorse the same conclusion of no clear relationship between energy quantity and economic growth.

Different reasons for this lack of relationship could be invoked. It may be due to the selected sample. Indeed, the relationship could be different depending on the countries, regions, sectors, or industries selected; but also for different periods of time. This problem dates to the seminal papers of Kraft and Kraft (1978) and Akarca and Long (1980). Also, it may be due to how energy is measured. Different measures, such as energy consumption (Liu (2009), Ghosh and Kanjilal (2014), Appiah (2018), and Bakirtas and Akpolat (2018)), energy generation (Atems and Hotaling (2018), and Walheer (2018b)), oil (Bastianin, Galeotti and Maner (2017)), nuclear (Ozcan and Ari (2015)), and electricity (Acaravci and Ozturk (2010), and Apergis and Payne (2011a)), are used in practice. Note that energy consumption remains the most commonly measure used for empirical works; probably because it is the most natural. It is also the measure used in the initial paper of Kraft and Kraft (1978).

A second potential explanation for the lack of consensus is the model used. Well-established methods such as OLS regression, the Granger causality test (Granger (1969)), conventional VAR (Sims (1972)), ADF test (Dickey and Fuller (1979)), the cointegration test for VECM models (Engle and Granger (1987)), the Phillips and Perron (1988) test, the KPSS test (Kwiatkowski et al (1992)), the modified Granger causality test (Toda and Yamamoto (1995)), and the ARDL test (Pesaran, Shin and Smith (2001)), have been used. See Narayan and Smyth (2014) for a literature review of econometric methods used for the energy and economic growth nexus. More and more advanced and complex methods have been used, as in the works of Odhiambo (2009), Wesseh and Zoumara (2012) Zhao and Wang (2015), Pablo-Romero and Sanchez-Braza (2017), and Appiah (2018); but these did not help to reach a consensus about the energy-economic growth relatioship. Therefore, a natural question is whether econometric tools are the best choice (see Karanfil (2009) and Hajko (2017)), and whether alternative methods should be considered.

Next, the lack of consensus may also be attributed to important omitted variables in the studies. Indeed, most of the empirical works used bivariate or, at most, trivariate frameworks. Missing important variables could create a bias. This is even more important when relying on econometric methods. As such, multivariate frameworks seem to be a safer way to tackle the nexus. Recent works include those of Huang, Hwang and Yang (2008a, b), Menyah and Wolde-Rufael (2010), Kocaaslan (2013), Wandji (2013), Solarin (2014), and Bah and Azam (2017). Of course, including more variables requires, in general, more advanced techniques and making specific assumptions (in particular, for econometric methods).

Finally, a last reason is that other energy-related variables should be used instead of energy quantity, for example, energy price, energy expenditure, energy efficiency, or energy intensity. Hamilton (1983) was the first to study the connection between energy prices and economic growth. Recent works include those of Lardic and Mignon (2008) and Katircioglu et al (2015) for energy prices, and Murphy et al (2011), Lambert et al (2014), King, Maxwell and Donovan (2015), and Fizaine and Court (2017) for energy expenditure. For energy efficiency refer, for example, to Apergis et al (2015) and Rajbhandari and Zhang (2018); and for energy intensity to Choi, Park and Yu (2017).

2.2 Renewable and non-renewable energy

Given the lack of a clear relationship between energy quantity and economic growth, several empirical works have been conducted when partitioning energy into smaller dimensions. Great interest has been given to renewable energy (and thus to non-renewable energy). The reason is simple; the deployment of renewable energy sources can play a crucial role in reducing both greenhouse gas emissions and non-renewable energy dependency. This is also in line with recent policy implementations and regulations (such as the Kyoto Protocol, the Europe 2020 strategy, and the Paris Agreement). Nevertheless, non-renewable energy remains the main source in the global energy mix; probably due to lower prices, entry barriers, and market failures. Recent works include those of Apergis and Payne, (2010b, c, 2011b, 2012), Simsek and Simsek (2013), Apergis and Danuletiu (2014), and Maji (2015).

Unfortunately, the different issues raised previously for the energy and economic growth nexus also hold true when considering renewable or non-renewable energy. That is, diverse relationships between renewable energy, non-renewable energy, and economic growth have been found in the literature: a positive relationship, the lack of any link, as well as, a bidirectional relationship. As such, these empirical works give rise to new nexuses. For reviews refer, for example, to Adewuyi and Awodumi (2017), and Kahia, Ben Aissa and Lanouar (2017).

2.3 Energy as necessary condition to economic growth

Despite the lack of a clear relationship between energy (partitioned or not) and economic growth, it does not mean necessary that it is uninteresting to study how energy contributes to economic growth. Indeed, another option is to acknowledge the importance of energy to economic growth by including energy quantity as a production factor. In other words, energy is seen as a pre-condition for economic activity and generating growth. In the case of scarcity, energy could put strong constraints on economic activity. In fact, this is a simple application of the law of thermodynamics to economic theory (see Georgescu-Roegen (1979) and Odum (1973) for earlier works; and Ayres and Warr (2009), Kummel (2011), and Hall and Klitgaard (2012) for reviews).

As such, several works have included energy in the production function. Refer, for example, to Stern (1993, 2000, 2011), Schou (2000), Le Kama and Schubert (2004), Lee (2005), Ricci (2007), Apergis and Payne (2010b), Acemoglu et al. (2012), Lin, Chen, and Chen (2013), Fallahi and Voia (2015), Calel and Dechezlepretre (2016), Esso and Keho (2016), Ott and Soretz (2016), Bretschger et al (2017), Bretschger and Schaefer (2017), Du and Lin (2017), and Costa-Campi, Garca-Quevedo and Trujillo-Baute (2018). These works differ in the way of including energy, but they all have in common the inclusion of energy as a production factor (an input). Note that these works also include more standard production factors, such as capital and labour. A simple reason is, as explained previously, to avoid bias of omitted variables.

Another option is to opt for a nonparametric approach. Indeed, choosing a specific parametric form for the production function when energy is involved could be rather complex in practice. This is also highlighted by the different modellings suggested. More importantly, choosing a production function may also have a huge impact on the estimation and thus on the results. Opting for a nonparametric approach offers the advantage of avoiding making a particular choice for the production function. Instead, the technology is reconstructed using (only) the data. This spirit has been used in, for example, Zhang et al (2011), Bampatsou, Papadopoulos and Zervas (2013), Song et al (2013), Wang, Lu and Wei (2013), Cherchye et al (2014), Apergis et al (2015), Wang and Feng (2015), and Cantore, Cali and te Velde (2016). At this point, we remark that the nonparametric approach also comes with a drawback. As the data are used to reconstruct the technology, outliers or measurement errors could create a bias in the reconstruction. Fortunately, different methods have been introduced to control for this type of issue (see Daraio and Simar (2007) and Section 4).

3 Methodology

In this Section, we start by defining the technology. As discussed in the Introduction, we adopt a nonparametric reconstruction of the technology in the sense that we only rely on what we observe instead of imposing specific assumptions on the growth process. Then, building on the reconstructed technology, we define our output efficient measurement. This measurement will be used to decompose labour productivity into six components.

3.1 Technology and output efficiency measurement

We consider that countries produce output Y using five production factors (or inputs): labour L, capital K, human capital H, renewable energy E, and non-renewable energy P. We also assume that human capital enters the technology as a multiplicative augmentation of labour input, i.e. $\hat{L} = H \times L$. This assumption is adopted in the previous works of Henderson and Russell (2005) and the followers (Badunenko, Henderson and Russell (2013), Walheer (2016a, b), etc.). Therefore, the production function is given by $Y(\hat{L}, K, E, P)$. Equivalently, the production function defines the following production possibility set:

$$T = \Big((Y, \hat{L}, K, E, P) \in \mathbb{R}^5_+ \mid Y \leq Y(\hat{L}, K, E, P)\Big) \tag{1}$$

As such, there is a one-to-one relationship between the production function $Y(\hat{L}, K, E, P)$ and the production possibility set T. In other words, defining the production function

$Y(\hat{L}, K, E, P)$ implies defining the production possibility set T, and reciprocally.

We adopt a nonparametric approach meaning that we reconstruct the technology using only the available data. In particular, we consider that we observe a sample of J countries during T periods of time. That is, we observe the following data set D:

$$D = \{(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt}) \mid j = 1, \ldots, J; t = 1, \ldots, T\} \tag{2}$$

where $\hat{L}_{ijt} = H_{jt} \times L_{ijt}$, as explained previously.

To avoid a trivial reconstruction and to match with previous works on economic growth modelling, we assume that the production function $Y(\hat{L}, K, E, P)$ is quasi-concave, continuous, strictly increasing, and satisfies constant returns-to-scale (note that those assumptions are not crucial for the following methodology and could be removed or modified if necessary, see Section 4). These assumptions on the production function imply that the production possibility set T is monotone, convex and satisfies constant returns-to-scale technology. We adopt a reconstruction of the production possibility set T that precludes technological degradation. This way to reconstruct the production possibility set, suggested by Diewert (1980) and used by Henderson and Russell (2005) and followers in similar contexts, avoids an implosion of the frontier (i.e. the boundary of the production possibility set T). In particular, the reconstructed production possibility set for country j at period t is given by:

$$T_t(D) = \left(\begin{array}{c} (Y, \hat{L}, K, E, P) \mid Y \leq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} Y_{j\tau}, \\ \hat{L} \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} \hat{L}_{j\tau}, \\ K \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} K_{j\tau}, \\ E \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} E_{j\tau}, \\ P \geq \sum_{\tau=1}^{t} \sum_{j=1}^{J} \lambda_{j\tau} P_{j\tau}, \\ \lambda_{j\tau} \geq 0 \ \forall j, \forall \tau. \end{array} \right) \tag{3}$$

Building on our reconstruction of the technology $T_t(D)$, we use a Debreu (1951)−Farrell (1957) output efficiency measurement to capture the maximal expansion of the output (keeping the inputs constant) for each country j at time t, defined as:

$$TE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt}) = \min \left\{ \eta \mid \left(\frac{Y_{jt}}{\eta}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt} \right) \in T_t(D) \right\} \tag{4}$$

$TE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt})$ is the inverse of the maximal amount that output Y_{jt}

can be expanded while keeping the inputs constant. Geometrically, $TE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt})$ measures the radial distance between the output quantity of country j at time t and the reconstructed frontier (i.e. the boundary of the production possibility set $T_t(D)$ for country j). $TE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt}) \leq 1$ and $TE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt}) = 1$ means that country j produces the maximal amount of output at time t. A smaller value of $TE_{jt}(Y_{jt}, \hat{L}_{jt}, K_{jt}, E_{jt}, P_{jt})$ implies more inefficient behaviour.

3.2 Decomposition of Labour Productivity Growth

We show how the growth of labour productivity can be decomposed into six parts: (1) efficiency change (EFF), (2) technological change ($TECH$), (3) physical capital change ($KACC$), (4) human capital change ($HACC$), (5) renewable energy change ($EACC$), and (6) non-renewable energy change ($PACC$). The first three parts have been introduced by Kumar and Russell (2002) while the fourth component is due to Henderson and Russell (2005). The novelty is captured by the last two parts that isolate the contribution of each type of energy to the labour productivity growth. In the rest of this section, we drop the subscript j (referring to a specific country) for better readability.

As we are interested by the decomposition of labour productivity $y_t = Y_t/L_t$, it is more convenient to define variables per worker. Moreover, building on our constant returns-to-scale assumption of the technology, this will also imply that we can move from a representation in five dimensions $\langle Y_t, \hat{L}_t, K_t, E_t, P_t \rangle$ to a representation in four dimensions $\langle \hat{y}_t, \hat{k}_t, \hat{e}_t, \hat{p}_t \rangle$, simply by defining $\hat{y}_t = Y_t/\hat{L}_t$, $\hat{k}_t = K_t/\hat{L}_t$, $\hat{e}_t = E_t/\hat{L}_t$, and $\hat{p}_t = P_t/\hat{L}_t$. As such, the production function $\hat{y}_t(\hat{k}_t, \hat{e}_t, \hat{p}_t)$ characterizes the technology (note that the subscript t on $\hat{y}$ refers to the year of the technology).

Without loss of generality, we assume that we are interested by decomposing the labour productivity growth between period b (the base period) and period c (the current period). As such, the aim is to decompose $\frac{y_c}{y_b}$ into the six components defined before.

We denote the efficient output at time b and c by: $\hat{y}_b(\hat{k}_b, \hat{e}_b, \hat{p}_b) = \hat{y}_b/\theta_b$ and $\hat{y}_c(\hat{k}_c, \hat{e}_c, \hat{p}_c) = \hat{y}_c/\theta_c$, where $\theta_t = TE_t(Y_t, \hat{L}_t, K_t, E_t, P_t)$ for $t = \{b, c\}$. We could then define the following equality:

$$\frac{\hat{y}_c}{\hat{y}_b} = \frac{\theta_c}{\theta_b} \frac{\hat{y}_c(\hat{k}_c, \hat{e}_c, \hat{p}_c)}{\hat{y}_b(\hat{k}_b, \hat{e}_b, \hat{p}_b)} \tag{5}$$

Using the fact that growth of labour productivity is equal to the growth of human capital multiplied by the growth of output per efficiency unit of labour, we obtain:

$$\frac{y_c}{y_b} = \frac{H_c}{H_b}\frac{\hat{y}_c}{\hat{y}_b} \tag{6}$$

$$= \frac{H_c}{H_b}\frac{\theta_c}{\theta_b}\frac{\hat{y}_c(\hat{k}_c, \hat{e}_c, \hat{p}_c)}{\hat{y}_b(\hat{k}_b, \hat{e}_b, \hat{p}_b)} \tag{7}$$

The next step is more complex. In order to isolate the effect of each component, we define new variables under the counterfactual assumption that human capital has not changed. In particular, we define $\tilde{k}_c = K_c/(L_cH_b)$, $\tilde{e}_c = E_c/(L_cH_b)$, and $\tilde{p}_c = P_c/(L_cH_b)$ as the ratio of capital to labour, the ratio of renewable energy to labour, and the ratio of non-renewable energy to labour, under the counterfactual assumption that human capital has not changed from its base period. In a similar vein, we define $\tilde{k}_b = K_b/(L_bH_c)$, $\tilde{e}_b = E_b/(L_bH_c)$, and $\tilde{p}_b = P_b/(L_bH_c)$, as the ratio of capital to labour, the ratio of renewable energy to labour, and the ratio of non-renewable energy to labour, under the counterfactual assumption that human capital is equal to its current period level.

Multiplying equation (7) by $\frac{\hat{y}_c(\hat{k}_b,\hat{e}_b,\hat{p}_b)}{\hat{y}_c(\hat{k}_b,\hat{e}_b,\hat{p}_b)}$, $\frac{\hat{y}_c(\tilde{k}_b,\hat{e}_c,\hat{p}_c)}{\hat{y}_c(\tilde{k}_b,\hat{e}_c,\hat{p}_c)}$, $\frac{\hat{y}_c(\tilde{k}_b,\tilde{e}_b,\tilde{p}_b)}{\hat{y}_c(\tilde{k}_b,\tilde{e}_b,\tilde{p}_b)}$, and $\frac{\hat{y}_c(\tilde{k}_b,\hat{e}_c,\tilde{p}_b)}{\hat{y}_c(\tilde{k}_b,\hat{e}_c,\tilde{p}_b)}$, and rearranging the terms gives us:

$$\frac{y_c}{y_b} = \frac{\theta_c}{\theta_b}\frac{\hat{y}_c(\hat{k}_b, \hat{e}_b, \hat{p}_b)}{\hat{y}_b(\hat{k}_b, \hat{e}_b, \hat{p}_b)}\frac{\hat{y}_c(\hat{k}_c, \hat{e}_c, \hat{p}_c)}{\hat{y}_c(\tilde{k}_b, \hat{e}_c, \hat{p}_c)}\left(\frac{\hat{y}_c(\tilde{k}_b, \tilde{e}_b, \tilde{p}_b)}{\hat{y}_c(\hat{k}_b, \hat{e}_b, \hat{p}_b)}\frac{H_c}{H_b}\right)\frac{\hat{y}_c(\tilde{k}_b, \hat{e}_c, \tilde{p}_b)}{\hat{y}_c(\tilde{k}_b, \tilde{e}_b, \tilde{p}_b)}\frac{\hat{y}_c(\tilde{k}_b, \hat{e}_c, \hat{p}_c)}{\hat{y}_c(\tilde{k}_b, \hat{e}_c, \tilde{p}_b)} \tag{8}$$

$$= EFF \times TECH^b \times KACC^c \times HACC^c \times EACC^c \times PACC^c \tag{9}$$

For each term, only the variable under interest changes from the denominator to the numerator. For example, for $KACC^c = \frac{\hat{y}_c(\hat{k}_c,\hat{e}_c,\hat{p}_c)}{\hat{y}_c(\tilde{k}_b,\hat{e}_c,\hat{p}_c)}$, only capital has changed, $\tilde{k}_b$ to $\hat{k}_c$, while all the other variables are constant. As such, $KACC^c$ captures the contribution of capital change on labour productivity growth. The same reasoning could be used for the four other components. Finally, note that the postscript c on $KACC$ means that the technology is fixed at the current period.

In equations (8) and (9), we fix the technology to year c. Similarly, we could fix the technology to year b. It suffices to multiply equation (7) by $\frac{\hat{y}_b(\hat{k}_b,\hat{e}_b,\hat{p}_b)}{\hat{y}_b(\hat{k}_c,\hat{e}_c,\hat{p}_c)}$, $\frac{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\hat{p}_b)}{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\hat{p}_b)}$,

$\frac{\hat{y}_b(\tilde{k}_c,\tilde{e}_c,\tilde{p}_c)}{\hat{y}_b(\tilde{k}_c,\tilde{e}_c,\tilde{p}_c)}$, and $\frac{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\tilde{p}_c)}{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\tilde{p}_c)}$. By rearranging the terms, we have:

$$\frac{y_c}{y_b} = \frac{\theta_c}{\theta_b}\frac{\hat{y}_c(\hat{k}_c,\hat{e}_c,\hat{p}_c)}{\hat{y}_b(\hat{k}_c,\hat{e}_c,\hat{p}_c)}\frac{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\hat{p}_b)}{\hat{y}_b(\hat{k}_b,\hat{e}_b,\hat{p}_b)}\left(\frac{\hat{y}_b(\hat{k}_c,\hat{e}_c,\hat{p}_c)}{\hat{y}_b(\tilde{k}_c,\tilde{e}_c,\tilde{p}_c)}\frac{H_c}{H_b}\right)\frac{\hat{y}_b(\tilde{k}_c,\tilde{e}_c,\tilde{p}_c)}{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\tilde{p}_c)}\frac{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\tilde{p}_c)}{\hat{y}_b(\tilde{k}_c,\hat{e}_b,\hat{p}_b)} \tag{10}$$

$$= EFF \times TECH^c \times KACC^b \times HACC^b \times EACC^b \times PACC^b \tag{11}$$

As such, we obtain two alternative decompositions of the labour productivity growth when we take year c or b as the reference year for the technology. Note that the two decompositions are equal only if the neutrality of technological change is assumed (as in Solow (1957) and followers), but we do not want to make this restrictive assumption. To overcome the path dependence of the decomposition, Kumar and Russell (2002), Henderson and Russell (2005) and followers have suggested adopting the Fisher Ideal decomposition introduced by Caves, Christensen and Diewert (1982) and Färe et al. (1994). In particular, multiplying equations (9) and (11) and taking the geometric average yield:

$$\begin{aligned}\frac{y_c}{y_b} = {} & EFF \times \left(TECH^b \times TECH^c\right)^{1/2} \times \left(KACC^b \times KACC^c\right)^{1/2} \\ & \times \left(HACC^b \times HACC^c\right)^{1/2} \times \left(EACC^b \times EACC^c\right)^{1/2} \times \left(PACC^b \times PACC^c\right)^{1/2}\end{aligned} \tag{12}$$

$$= EFF \times TECH \times KACC \times HACC \times EACC \times PACC \tag{13}$$

We obtain the desired decomposition of labour productivity change into the efficiency change (EFF), the geometric averages (over the base and current periods) of technological change ($TECH$), physical capital change ($KACC$), human capital change ($HACC$), renewable energy change ($EACC$), and non-renewable energy change ($PACC$).

4 Application

To present our application, we first explain how the data are selected and give some descriptive statistics. Subsequently, we give the results of the empirical analysis.

4.1 Data and descriptive statistics

In this section, we first explain how we measure the six variables and then present some descriptive statistics.

4.1.1 Data

We use the *EUROSTAT* database for the data of output (Y), capital (K), labour (L); and the *OECD* database for the data of energy and renewable energy consumption (E). Non-renewable energy consumption (P) is obtained as the difference between energy and renewable energy consumption. Output and capital are measured in millions of the current national currency, labour in thousands of people employed, renewable and non-renewable energy in tons of oil equivalent. Human capital (H) is constructed following the Hall and Jones (1999) procedure:

$$H_{jt} = e^{\gamma(u_{jt})} \tag{14}$$

where γ is a piecewise-linear function, with a zero intercept and a slope of 0.134 through the fourth year of education, 0.101 for the next 4 years, and 0.068 for education beyond the eighth year; and u_{jt} is the average number of years of education of the adult population in country j at time t given by Barro and Lee (2013).

We correct output and capital by inflation and by purchasing power parity (PPP); data of these two variables have also been taken from the *EUROSTAT* database, to obtain comparable data. Consequently, output and capital are measured in constant PPP prices (we choose 1995 as the reference year since it is the first year of our sample). No correction is needed for the other variables.

We select the biggest sample possible which consists of 26 European countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Romania, United Kingdom, Slovakia, Slovenia, Spain, and Sweden. The time period is 1995-2015.

4.1.2 Descriptive statistics

In Table 1, we present the descriptive statistics for our variables. We compute the median growth of each variable between 1995 and 2015 (see column 2); we prefer the medians rather than the means given their robustness feature. Firstly, output growth has contributed more to labour productivity growth than labour growth. Next, capital accumulation has more than doubled in 20 years, which highlights its major role. Afterwards, augmented labour growth is more important than labour growth, meaning that human capital accumulation has a positive role on that period. Finally, renewable energy growth is positive and very important, probably because the level in 1995 was very low, while non-renewable growth is negative; total energy is very stable for that period. This means that renewable to non-renewable ratio growth has more than tripled in 20 years. This energy mix change also highlights the willingness of the European countries to meet recent policy and regulatory implementations (such as the Kyoto Protocol, the Europe 2020 strategy, and the Paris Agreement). Therefore energy is an important aspect when evaluating economic growth and convergence of those countries.

Table 1: Median growths and relative shares (in %)

Group	**Europe**	**EU12**		**Eastern and central Europe**	
Variable	Growth	Growth	Share	Growth	Share
Y	62.49	44.49	90.19	80.48	9.81
L	13.52	19.84	78.35	7.19	21.65
Y/L	23.87	17.55	71.34	80.74	28.66
K	111.62	49.43	89.32	173.80	10.68
$\hat{L}$	23.55	32.62	77.85	14.49	22.15
E	219.66	288.02	79.10	151.30	20.90
P	-8.78	-7.19	81.35	-10.37	18.65
$E+P$	0.47	3.03	81.14	-2.07	18.86
E/P	266.57	334.95	-	198.19	-

Next, we make a distinction between two groups: EU12 and Eastern and central Europe. Eastern and central Europe include Austria, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia. EU12 includes the other countries. At this point, this distinction could seem arbitrary, even if it is common to divide Europe into old and new members, but as shown below it is clear that there are two groups in terms of economic growth and convergence in Europe. Table 1 contains the median growth of our variables for each group (columns 2 and 4), and the relative share of each group for every variable (columns 3 and 5). Firstly, labour productivity growth is more important for Eastern and central Europe than for EU12, due to a larger output growth. Next, capital accumulation is clearly greater in Eastern and central Europe than in EU12, while augmented labour growth is smaller. Finally, non-renewable energy growth is smaller in Eastern and central Europe but renewable energy growth is larger, while total energy has increased for EU12 and decreased for Eastern and central Europe. The share for EU12 is around 80-90 for all the variables, meaning that those countries are the more important in Europe.

While these descriptive statistics show some important patterns and already highlight major differences between these two groups, they are only descriptive and should therefore be interpreted carefully. They do not show how each variable contributes to the growth and the convergence of the European countries, and whether the contributions of each variable are different for each group. This is the aim of the next Section.

4.2 Results

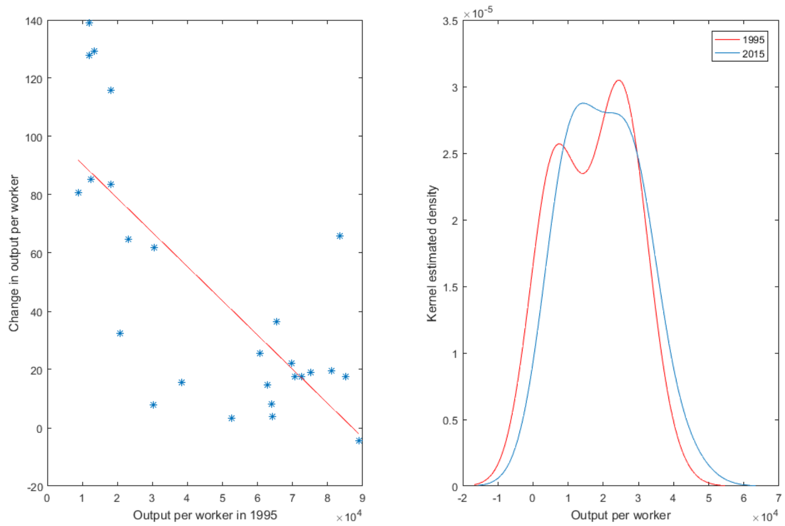
This Section is divided into two parts. Firstly, we determine the role of energy use, by making a clear distinction between renewable and non-renewable energy, in the economic growth and convergence of the European countries. Next, we investigate the relationships between energy index changes and several variables.

4.2.1 Role of energy in the growth and the convergence

As a first step, we investigate whether European countries converge or diverge in terms of output per worker. The regression line in Figure 1 (left) presents the change in output per worker (between 1995 and 2015) against the output per worker level in 1995. The significant negative slope (GLS t-stat of -11.17) reveals that countries with a lower initial output per worker level have a larger economic growth, which implies a convergence in terms of economic growth of the European countries. Also, on this graph, we can point out two groups: on the left the Eastern and central European countries and on the right EU12 countries. By looking more in detail at each group separately, we see that in the Eastern and central European countries, four countries (on the upper left corner) have relatively better performances (i.e. better than the regression line): Slovakia, Latvia, Estonia, and Lithuania. By way of contrast, three countries (on the lower left and middle corners) have relatively worse performances:

Cyprus, Croatia, and Hungary. Finally, only one country presents relatively better performances in the EU12 group (on the upper right corner): Ireland.

Figure 1: Output per worker: regression and distribtions



To confirm our findings based on the regression line, in Figure 1 (right) we plot, the distribution of output per worker in 1995 and 2015. The distribution in 1995 seems to be bimodal while the distribution of 2015 appears to be unimodal, speaking in favour of the existence of two groups that converge. To confirm our observations, we use Silverman's (1981) test: the null hypothesis is that a kernel distribution has q modes and the alternative hypothesis is that it has more than q modes. This test confirms our first observation: the 1995 distribution contains at least two modes (p-value=0.018), but no more than three (p-value=0.3245), while the 2015 distribution contains at least one mode (p-value=0.0230), but no more than two (p-value=0.4924).

Next, we investigate the role of the six components in the convergence of the European countries. The main interest for us is the contributions of non-renewable and renewable energy. In a sense, the other components are present to avoid the bias of omitted variables in our analysis and to verify that their impacts are as expected (as such, they also play a role of control variables, see Section 2). We present in Table 2 the medians of the percentage change of each index (again, we prefer the medians rather than the means given their robustness feature) of the decomposition for all the countries and the two groups identified previously.

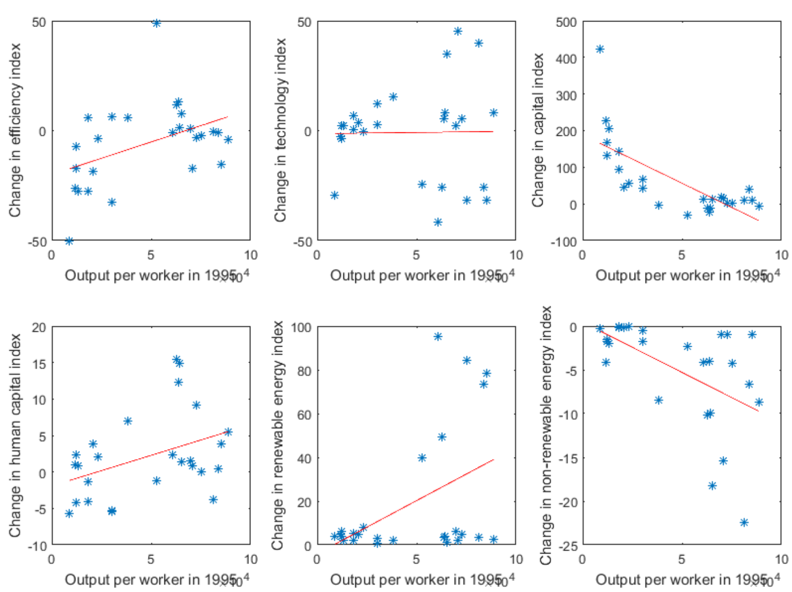
Clearly, the main driver of economic growth, as already shown in Table 1, is

Table 2: Medians of the decomposition per group (in %)

Group	PROD	EFF	TECH	KACC	HACC	EACC	PACC
All European countries	23.87	-2.75	4.88	13.83	1.16	2.89	-1.81
Eastern and central Europe	80.74	-17.42	10.59	25.69	1.15	0.81	-0.48
EU12	17.55	-0.40	5.47	0.98	3.83	3.79	-6.62

capital accumulation while technological change comes in second. Human capital accumulation and renewable energy change have smaller positive roles. Both efficiency and non-renewable energy changes have negative roles. Renewable energy and non-renewable energy changes have small, but non-negligible opposite effects on the economic growth. Moreover, the amplitude is different for each group. For Eastern and central European countries, both energy changes have small impacts but renewable energy changes compensate for non-renewable energy changes. For EU12 countries both energy changes have larger impacts and non-renewable energy changes do not compensate for renewable changes. These results are very general since they are only based on the medians. Figure 2 gives more details by plotting the change in the six components against the initial output per worker level for all the countries.

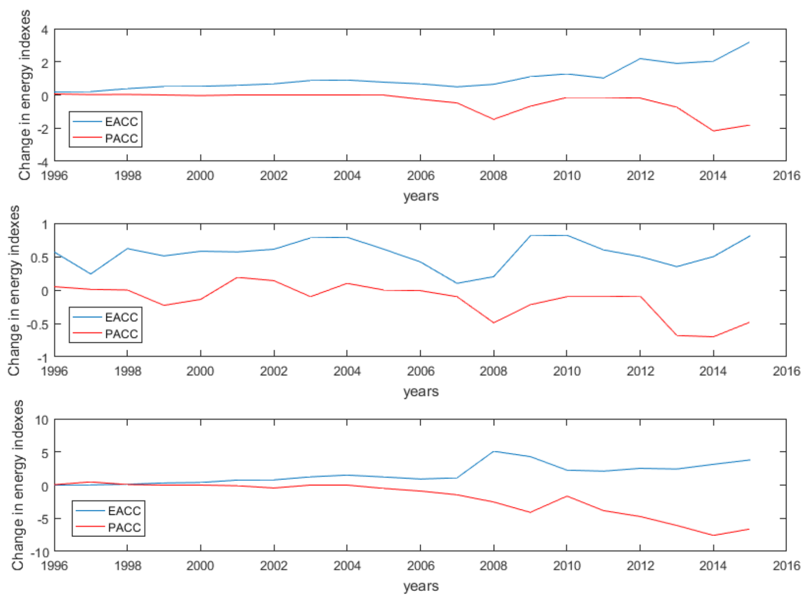
Figure 2: Role of the six components in the convergence



A negative slope indicates that the component has contributed to the divergence between countries. A positive slope indicates the opposite. Except for the changes in technology index, all slopes are significant (GSL t-stats of 4.8585, 0.1347, -10.3925, 4.3898, 5.2882, and -5.7245). As such, technical efficiency, human capital, and non-renewable energy changes contribute to the divergence between countries, while capital and renewable energy changes have contributed to the convergence between countries. Non-renewable and renewable energy changes have opposite sign effects on economic growth: non-renewable energy has a positive impact implying a divergence between countries, while renewable energy has a negative impact implying a convergence between countries. Also, for some countries, mostly at a lower level of initial output per worker, changes in energy indexes have small, if any, impacts on the economic growth, while, for other countries, mostly at a higher level of initial output per worker, changes in energy indexes have more important impacts (we also noticed this in Table 2). At this point, it is important to highlight that the non-renewable index change is always negative while the renewable index change is always positive. (This is in line with the descriptive statistics in Table 1). As such, the divergence caused by non-renewable energy index changes means that richer countries benefit more from that type of energy in terms of labour productivity growth, while the convergence caused by the renewable energy index changes means that richer countries have faced a contraction of labour productivity.

The questions are therefore whether the impacts of non-renewable and renewable energy compensate for each other on the period ? What is the impact of total energy on economic growth and convergence ? And are the energy impacts stable for the period ? To tackle these questions, we plot renewable and non-renewable energy changes for each year (i.e. from 1996 to 2015) for all countries (Figure 3 top) but also by distinguishing the two groups (Figure 3 middle for Eastern and central European countries and Figure 3 bottom for EU12 countries). We show that the impact of energy changes on the economic growth clearly implodes over time, probably due to the recent policy and regulatory implementations leading to change in energy mix and energy investment behaviours (see Section 3.2.2). Also, the impact of renewable energy changes compensate for the impact of non-renewable energy changes on that period, meaning that total energy has caused a divergence between countries. Next, as already shown in both Table 2 and Figure 2, the amplitude is clearly different for the two groups; for Eastern and central European countries the impacts are more or less constant for the period, while for EU12 countries the impacts have imploded over time. Also, the impacts on the economic growth of renewable energy changes compensate for those of non-renewable energy changes for the Eastern and central European countries, but for the EU12 countries, this is not true after 2011. It suggests that before 2011, energy changes imply a divergence for that group, while after 2011 it implies a convergence (i.e. an output contraction).

Figure 3: Changes in energy indexes



Finally, to highlight once more the importance of energy in the decomposition, we compare our methodology with the two previous methods of Kumar and Russell (2002) and Henderson and Russell (2005). Results are displayed in Table 3.

Even if other studies do not consider exactly the same set of countries (OECD or less European countries), the comparison reveals that our results are consistent with previous studies. All these works confirm our main results: capital accumulation and technological change have played the most important roles in the convergence and human capital accumulation cannot be omitted since it also plays an important role. Our replications also reveal interesting results. Firstly, both decompositions indicate once more that capital accumulation and technological change have played the greatest roles in the convergence. Next, when adding human capital, the roles of both capital accumulation and technological change decrease. Finally, if we compare this last case when adding energy use, we see that technological change decreases significantly and both capital and human capital decreases. All in all, it advocates

Table 3: Comparisons and replications

	Period	**PROD**	**EFF**	**TECH**	**KACC**	**HACC**	**EACC**	**PACC**
This paper	1995-2015	23.87	-2.75	4.88	13.83	1.16	2.89	-1.81
W(a)	1995-2014	18.89	-9.54	5.14	9.14	16.73	-	-
W(b)	1995-2008	14.19	-18.86	12.27	20.14	8.91	-	-
BHZ	1992-2000	20.25	-4.88	22.33	3.34	-	-	-
HR	1965-1990	83.3	0.4	14.3	39.5	14.8	-	-
BHR	1965-2007	142.8	9.4	36.2	26.1	25.7	-	-
This paper	1995-2015	23.87	-2.91	8.10	14.85	2.15	-	-
This paper	1995-2015	23.87	-2.94	10.52	16.12	-	-	-

W(a): Walheer (2016a); W(b): Walheer (2016b) BHZ: Badunenko, Henderson and Zelenyuk (2008); HR: Henderson and Russell (2005); BHR: Badunenko, Henderson and Russell (2013).

taking energy use into account when analysing economic growth and convergence.

We end this part by two remarks. One, we point out that, as discussed in Section 2, a drawback of the production-frontier approach is its sensitivity to outliers and measurement errors. Indeed, all observations are used to reconstruct the technology (see (3)). Therefore, to control for potential issues, we make used of a robust method (see Daraio and Simar (2007)). Interestingly, the robust method does not clearly highlight for potential issues, but reveals that the countries in the EU12 group are clearly above the other European countries in terms of output performance. Two, we remark that other grouping methods can be used for the countries. The one used on the paper comes from both our observation from Figure 1 and a natural distinction between rich and poor (or new and old) European members. We may wish to use, for example, the economic growth rates, the growth rate of renewable energy, or the stringency of their energy targets for grouping the countries. Note that we have tested for alternative grouping procedures, and most of our results remain valid.[2]

4.2.2 Understanding the differences in energy index changes

In this Section, we relate the energy index changes to several variables. The aim is to try to better understand the differences in energy index changes highlighted previously. Firstly, we relate our findings to the greenhouse gas emission growth, and the output per greenhouse gas emission growth. The use of energy as an input gives rise to greenhouse gas emissions, which are undesirable side-products of economic

[2]Robust estimation results and results for alternative grouping methods are not included in the paper for the sake of compactness. They are available on request to the author.

growth.[3] Next, we relate our findings to renewable to non-renewable ratio growth. European countries have put a lot of effort into decreasing non-renewable energy and increasing renewable energy, resulting in an important change in that ratio (see also Table 1). Finally, we relate energy index changes to the energy-related targets of the Europe 2020 strategy. Policy and regulatory implementations are perhaps the main reason why European countries have changed their energy mix and energy investment behaviours.

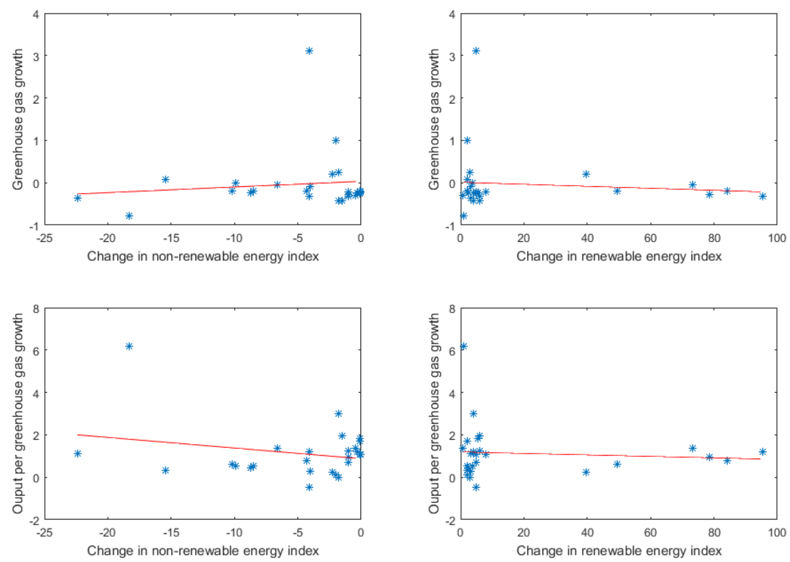
We plot, in Figure 7 available in the Appendix, the growth of greenhouse gases and the output per greenhouse gas growth for all European countries (top), Eastern and central European countries (middle) and EU12 countries (bottom).[4] The greenhouse gas emission growth is not always negative for the European countries while the average is: -1.20 % per year. Output per greenhouse gas emission growth is positive except for 2002, 2003, 2010 and 2013, with an average of 4.69% per year. Greenhouse gas emissions per group follow a very similar pattern with an average of -1.08 % per year for Eastern and central European countries, and an average of -1.24 % per year for EU12. For output per greenhouse gas growth the pattern is also quite similar for the two groups. For Eastern and central European countries, the average is 4.69 % with two important reductions in 2002 and 2010. For EU12, the average is 5.7% with important decreases in 2002, 2003, 2010 and 2013. In Figure 4, we present four graphs capturing the relationships between changes in energy indexes and the two variables discussed before.

The slopes are close to zero for the four cases and not significant (GLS t-tstat of 0.7535, -0.7051, -1.7168, and -0.4889, respectively), meaning that there are no clear connections between the changes in energy indexes and both the greenhouse gas emission growth and the output per greenhouse gas emission growth. This finding could be explained by the complex relationship between greenhouse gases, energy (renewable and non-renewable), and economic growth (see Section 2). Moreover, greenhouse gas emissions are the (undesirable) side-product feature of economic growth. That is, countries do not try to reduce them directly but they are reduced when non-renewable energy is decreased. Thus, the non-significant relationship argues for country-specific policies. On the four graphs, one country is clearly an outlier and could bias the

[3]See Cherchye, De Rock and Walheer (2015) for a recent review of efficiency models with bad or undesirable by-products, as greenhouse gases.

[4]Note that the final year is now 2014 due to availability of data for greenhouse gas emissions (taken also from the *EUROSTAT* database).

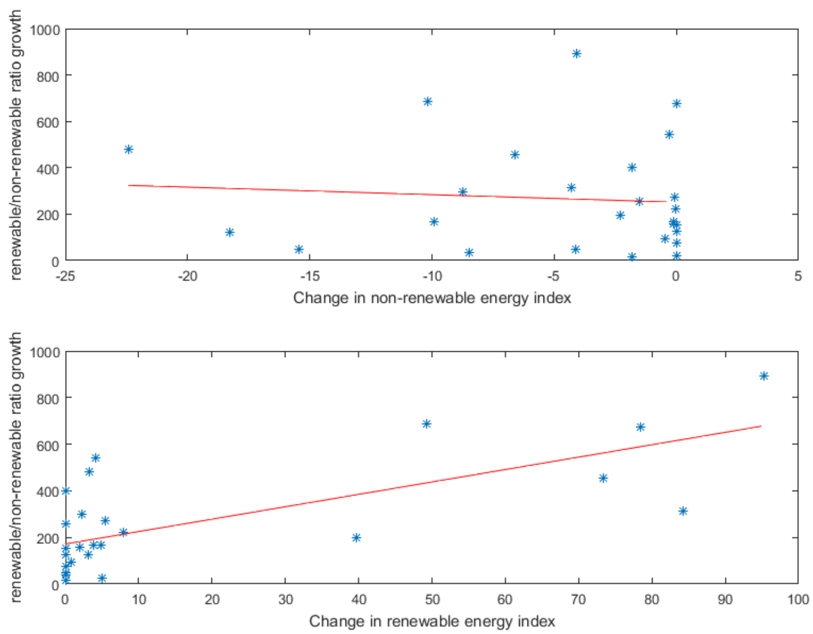
Figure 4: Energy indexes, greenhouse gas and output per greenhouse gas



regression slopes, this country is Latvia with a change in greenhouse gases of 311%. The four graphs without that country are available in Figure 8 in the Appendix. The slopes are still not significant (GLS t-tstat of 1.5040, -0.1899, -1.7046, -0.6872 respectively) and therefore our previous conclusions remain true.

Next, we investigate the relationships between the two energy index changes and the changes in renewable to non-renewable ratio growth. As shown in Figure 9 available in the Appendix, this ratio has clearly increased for the period 1995-2015 (from 5.72% to 15.96%). As before, we make a distinction between two groups: EU12 and Eastern and central European countries. EU12 has clearly a larger ratio (from 7.13% to 17.32%) than Eastern and central European countries (from 5.39% to 15.65%), but the change from 1995 to 2015 is very similar for the two groups (10.19 and 10.26 percentage points). We investigate in Figure 5 how the changes in this ratio are related to the changes in energy indexes. We find a negative, significant (GSL t-stat of -1.9517) slope for the relationship between renewable to non-renewable ratio growth and the changes in non-renewable index, meaning that larger changes in this index are associated with greater renewable to non-renewable ratio growth. The slope for the relationship between renewable to non-renewable ratio growth and the changes in renewable index is positive and significant (GSL t-stat of 5.8157) meaning that larger changes in the index are associated with larger renewable to non-renewable ratio growth. All in all, it means that increasing the renewable to non-renewable ratio is associated with larger changes in both renewable and non-renewable energy indexes; implying larger impacts of energy on economic growth. The impacts of total energy on economic growth is thus unclear and depend on the proportion of each energy type used to increase the renewable to non-renewable ratio.

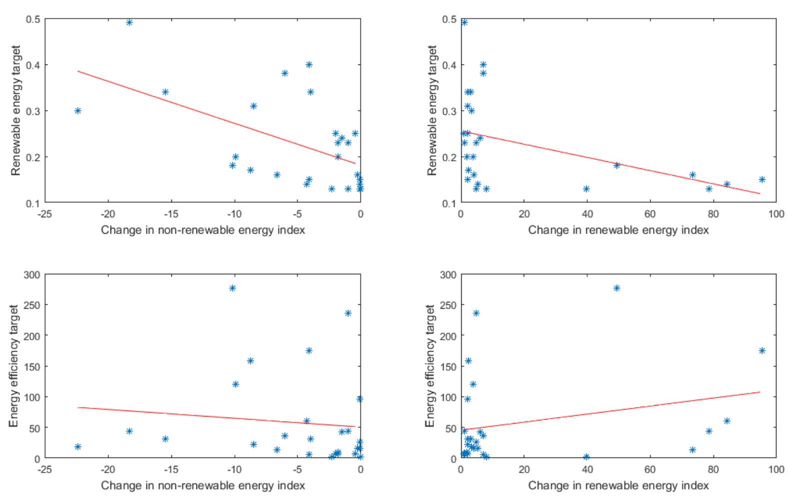
Figure 5: Output-capital graph in 1995 and 2014



Finally, we plot the changes in energy indexes against the energy-related targets of the Europe 2020 strategy: proportion of renewable energy target and energy efficiency target (Note that there are new more stringent targets for 2030). The renewable energy target is defined as a percentage of renewable energy with respect to the total energy use that should be reached by 2020. The energy efficient target is an objective in terms of primary energy consumption levels that European countries should achieve by 2020. These two targets are part of the Sustainable growth pillar of the Europe 2020 strategy. Note also that the target levels are country specific as set up by the Europe 2020 strategy (they are also given by *EUROSTAT*). For recent studies about the Europe 2020 strategy refer, for example, to Pasimeni and Pasimeni (2016), Rappai (2016), and Walheer (2017). These works have highlighted that countries have put much effort into reaching the targets of the Europe 2020 strategy, and, in particular the targets of the Sustainable growth pillar. They have revealed a difference in terms of performances between richer and poorer European countries. Of course, we might expect that this has a direct impact on economic growth (see Pasimeni and Pasimeni (2016)).

The slopes are negative and significant (GLS t-stat of -3.1222 and -3.0942, respectively) for the relationship between the renewable energy targets and the changes in energy indexes. It implies that larger renewable energy targets are associated with larger changes in the non-renewable energy index and smaller changes in the renewable energy index. Thus, larger renewable energy targets imply that, on average, the impact of total energy will be positive in terms of convergence between countries (by an output contraction of richer countries). In other words, there is a trade-off between economic growth and pursing the targets of the Sustainable growth pillar. For energy efficiency targets, the slope is negative but not significant (GLS t-stat of -0.7925) for the relationship with non-renewable energy index changes, and positive and not significant (GLS t-stat of 1.6626) for the relationship with renewable energy index changes. It means that larger energy efficiency targets imply larger changes in both non-renewable and renewable energy indexes, which have ambiguous effects on the impact of total energy on the economic growth and convergence of the European countries (as shown in Figures 2 and 3).

Figure 6: Energy indexes and the Europe 2020 objectives



5 Conclusion

Using a production-frontier approach, we assessed the contribution of both renewable and non-renewable energy to the economic growth of 26 European countries from 1995 to 2015. The distinguishing features of our methodology are that it does not require any assumptions about the growth process, and it isolates the impacts of renewable and non-renewable energy on labour productivity growth. We found that renewable energy and non-renewable energy changes have small but non-negligible opposite effects on economic growth: non-renewable energy has a positive impact implying a divergence between countries (richer countries benefit more from that type of energy), while renewable energy has a negative impact implying a convergence between countries (richer countries face a contraction of the growth). Next, we identified two groups within the European countries: Eastern and central Europe and EU12, and showed that the impacts of both types of energy are clearly different for each group. Finally, we related our findings to several variables and to the energy-related targets of the Europe 2020 strategy. This last part revealed important patterns and policy implications. In particular, it reveals that richer European countries have placed more emphasis on price incentives in order to foster the use of renewable energy and that such policies have a negative incidence on growth. It turns out that policy helps for poorer European countries may be needed to avoid a divergence in terms of energy mix in Europe.

References

[1] Acaravci A., Ozturk I., 2010, “Electricity consumption-growth nexus: evidence from panel data for transition countries”, *Energy Economics* 32 (3), 604-608.

[2] Acemoglu D., Aghion P., Bursztyn L., Hemous D., 2012, “The environment and directed technical change”, *American Economic Review* 102, 131-166.

[3] Adewuyi A. O., Awodumi O. B., 2017, “Renewable and non-renewable energy-growth-emissions linkages: Review of emerging trends with policy implications”, *Renewable and Sustainable Energy Reviews* 69, 275-291.

[4] Akarca A. T., Long T. V., 1980, “Relationship between energy and GNP: a reexamination”, *Journal of Energy Development* 5(2), 326-331.

[5] Apergis N., Aye G. C., Barros C. P., Gupta R., Wanke P., 2015, “Energy efficiency of selected OECD countries: A slacks based model with undesirable outputs”, *Energy Economics* 51, 45-53.

[6] Apergis N., Danuletiu D. C., 2014, “Renewable energy and economic growth: evidence from the sign of panel long-run causality”, *International Journal Energy Economic Policy* 4 (4), 578.

[7] Apergis N., Payne, J. E., 2010a, “A panel study of nuclear energy consumption and economic growth”, *Energy Economics* 32, 545-549.

[8] Apergis N., Payne, J. E., 2010b, “Renewable energy consumption and growth in Eurasia”, *Energy Economics* 32 (6), 1392-1397.

[9] Apergis N., Payne J. E., 2010c, “Renewable energy consumption and economic growth: evidence from a panel of OECD countries”, *Energy Policy* 38, 656-660.

[10] Apergis N., Payne J. E., 2011a, “A dynamic panel study of economic development and the electricity consumption-growth nexus”, *Energy Economics* 33 (5), 770-781.

[11] Apergis N., Payne J. E., 2011b, “The renewable energy consumption-growth nexus in Central America”, *Applied Energy* 88 (1), 343-347.

[12] Apergis N., Payne J. E., 2012, "Renewable and non-renewable energy consumption growth nexus: evidence from a panel error correction model", *Energy Economics* 34 (3), 733-738.

[13] Appiah M. O., 2018, "Investigating the multivariate Granger causality between energy consumption, economic growth and CO_2 emissions in Ghana", *Energy Policy* 112, 198-208.

[14] Atems B., Hotaling C., 2018, "The effect of renewable and nonrenewable electricity generation on economic growth", *Energy Policy* 112, 111-118.

[15] Ayres R. U., Warr B., 2009, "The Economic Growth Engine: How Energy and Work Drive Material Prosperity", *Edward Elgar Publishing Ltd* Cheltenham.

[16] Badunenko O., Henderson D. J., Russell R. R., 2013, "Polarization of the worldwide distribution of productivity", *Journal of Productivity Analysis* 40, 153-171.

[17] Badunenko O., Henderson D. J., Zelenyuk V., 2008, "Technological change and transition: relative contributions to worldwide growth during the 1990s", *Oxford Bulletin of Economics and Statistics* 70(4), 61-92.

[18] Badunenko O., Romero-Avila D., 2014, "Productivity Growth across Spanish Regions and Industries", *Regional Studies* 48, 1242-1262.

[19] Badunenko O., Tochkov K., 2010, "Soaring Dragons, Roaring Tigers, and Growling Bears: Determinants of Regional Growth and Convergence in China, India, and Russia", *Economics of Transition* 18, 539-570.

[20] Bah M. M., Azam M., 2017, "Investigating the relationship between electricity consumption and economic growth: Evidence from South Africa", *Renewable and Sustainable Energy Reviews* 80, 531-537.

[21] Bakirtas T., Akpolat A. G., 2018, "The Relationship between Energy Consumption, Urbanization, and Economic Growth in New Emerging-Market Countries", *Energy* forthcoming.

[22] Bampatsou C., Papadopoulos S., Zervas E., 2013, "Technical efficiency of economic systems of EU-15 countries based on energy consumption", *Energy Policy* 55, 426-434.

[23] Barro R. J., 1991, "Economic growth in a cross section of countries", *Quarterly Journal of Economics* 106, 407-443.

[24] Barro R. J., Lee J. W. 2013, "A new data set of educational attainment in the world", *Journal of Development Economics* 104, 184-198.

[25] Bastianin A., Galeotti M., Maner M., 2017, "Oil supply shocks and economic growth in the Mediterranean", *Energy Policy* 110, 167-175.

[26] Baumol W., 1986, "Productivity Growth, Convergence, and Welfare: What the Long-run Data Show", *American Economic Review* 76(5), 1072-1085.

[27] Bretschger L., Lechthaler F., Rausch S., Zhang L., 2017, "Knowledge diffusion, endogenous growth, and the costs of global climate policy", *European Economic Review* 93, 47-72

[28] Bretschger L., Schaefer A., 2017, "Dirty history versus clean expectations: Can energy policies provide momentum for growth?", *European Economic Review* forthcoming.

[29] Calel R., Dechezlepretre A., 2016, "Environmental policy and directed technological change: evidence from the European carbon market", *Review of Economics and Statistics* 98, 173-191.

[30] Cantore N., Cali M., te Velde D. W., 2016, "Does energy efficiency improve technological change and economic growth in developing countries?", *Energy Policy* 92, 279-285.

[31] Caves D. W., Christensen L. R., Diewert W. E., 1982, "The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity", *Econometrica* 50, 1392-1414.

[32] Chen P.-Y., Chen S.-T., Chen C.-C., 2012, "Energy consumption and economic growth - new evidence from meta-analysis", *Energy Policy* 44, 245-255.

[33] Cherchye L., De Rock B., Estache A., Walheer B., 2014, "Reducing Energy Use Without Affecting Economic Objectives: A Sectoral Analysis", in *The Next Generation of Economic Issues in Energy Policy in Europe*, CEPR Press.

[34] Cherchye L., De Rock B., Walheer B., 2015, "Multi-output efficiency with good and bad outputs", *European Journal of Operational Research* 240(3), 872-881.

[35] Choi B., Park W., Yu B.-K., 2017, "Energy intensity and firm growth", *Energy Economics* 65, 399-410.

[36] Costa-Campi M. T., Garca-Quevedo J., Trujillo-Baute E., 2018, "Electricity regulation and economic growth", *Energy Policy* 113, 232-238.

[37] Daraio C., Simar L., 2007, "Robust and Nonparametric Methods in Efficiency Analysis. Methodology and Applications", *Springer*.

[38] Debreu G., 1951, "The Coefficient of Resource Utilization", *Econometrica* 19(3), 273-292.

[39] Dickey D. A., Fuller W. A., 1979, "Distribution of the Estimators for Autoregressive Time Series with a Unit Root", *Journal of the American Statistical Association* 74 (366), 427-431.

[40] Diewert W., 1980, "Capital and the theory of productivity measurement.", *American Economic Review* 70(2), 260-267.

[41] Du K., Lin B., 2017, "International comparison of total-factor energy productivity growth: A parametric Malmquist index approach", *Energy* 118, 481-488.

[42] Enflo K., Hjertstrand P., 2009, "Relative Sources of European Regional Productivity Convergence: A Bootstrap Frontier Approach", *Regional Studies* 43(5), 643-659.

[43] Engle R., Granger C., 1987, "Co-integration and error correction: representation, estimation, and testing", *Econometrica* 2, 251-276.

[44] Esso L. J., Keho Y., 2016, "Heading Energy consumption, economic growth and carbon emissions: Cointegration and causality evidence from selected African countries", *Energy* 114, 492-497.

[45] Fallahi F., Voia M.-C., 2015, "Convergence and persistence in per capita energy use among OECD countries: Revisited using confidence intervals", *Energy Economics* 52, 246-253.

[46] Färe R., Grosskopf S., Margaritis D., 2006, “Productivity Growth and Convergence in the European Union”, *Journal of Productivity Analysis* 25(1), 111-141.

[47] Färe R., Grosskopf S., Margaritis D., 2007, “Productivity, convergence and policy: a study of OECD countries and industries”, *Journal of Productivity Analysis* 28(1-2), 87-105.

[48] Färe R., Grosskopf S., Norris M., Zhang Z., 1994, “Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries”, *American Economic Review* 84 (1), 66-83.

[49] Farrell M., 1957, “The Measurement of Productive Efficiency”, *Journal of the Royal Statistical Society* Series 1, General, 120, Part 3, 253-281.

[50] Fizaine F., Court V., 2017, “Energy expenditure, economic growth, and the minimum EROI of society”, *Energy Policy* 95, 172-186.

[51] Galor O., 1996, “Convergence? inferences from theoretical models”, *Economic Journal* 106, 1056-1096.

[52] Georgescu-Roegen N., 1979, “Energy analysis and economic valuation”, *Southern Economic Journal* 45,1023-1058.

[53] Ghosh S., Kanjilal K., 2014, “Long-term equilibrium relationship between urbanization, energy consumption and economic activity: Empirical evidence from India”, *Energy* 66, 324-331.

[54] Granger C. W., 1969, “Investigating causal relations by econometric models and crossspectral methods”, *Econometrica* 3, 424-438.

[55] Hajko V., 2017 “The failure of Energy-Economy Nexus: A meta-analysis of 104 studies”, *Energy* 125, 771-787.

[56] Hall R., Jones C., 1999, “Why do some countries produce so much more output per worker than others”, *Quarterly Journal of Economics* 114(1), 83-116.

[57] Hall C. A. S., Klitgaard K. A., 2012, “Energy and the Wealth of Nations: Understanding the Biophysical Economy”, *Springer* New York.

[58] Hamilton J. D., 1983, "Oil and the macroeconomy since World War II", *Journal of Political Economy* 91, 228-248.

[59] Henderson D. J., Russell R. R., 2005, "Human capital and convergence: a production-frontier approach", *International Economic Review* 46(4), 1167-1205.

[60] Henderson D. J., Parmeter C. F., Russell R. R., 2008 , "Modes, weighted modes, and calibrated modes: Evidence of clustering using modality tests", *Journal of Applied Econometrics* 23, 607-638.

[61] Huang B.-N.,Hwang M. J., Yang C. W., 2008a, "Causal relation between energy consumption and GDP growth revisited: a dynamic panel data approach", *Ecological Economics* 67(1), 41-54.

[62] Huang B.-N., Hwang M. J., Yang C. W., 2008b, "Does more energy consumption bolster economic growth? An application of the non linear threshold regression model", *Energy Policy* 36(2),755-767.

[63] Johnson P., 2005, "A continuous state space approach to convergence by parts", *Economics Letters* 86, 317-321.

[64] Jones C., 1997, "On the Evolution of the World Income Distribution", *Journal of Economic Perspectives* 11(3), 19-36.

[65] Kahia M., Ben Aissa, M. S., Lanouar C., 2017, "Renewable and non-renewable energy use - economic growth nexus: The case of MENA Net Oil Importing Countries", *Renewable and Sustainable Energy Reviews* 71, 127-140.

[66] Kalimeris P., Richardson C., Bithas K.,2014, "A meta-analysis investigation of the direction of the energy-GDP causal relationship: implications for the growth-degrowth dialogue", *Journal of Cleaner Production* 67, 1-13.

[67] Karanfil F., 2009, "How many times again will we examine the energy-income nexus using a limited range of traditional econometric tools?", *Energy Policy* 37 (4), 1191-1194.

[68] Katircioglu S. T., Sertoglu K., Candemir M., Mercan M., 2015 "Oil price movements and macroeconomic performance: evidence from twenty-six OECD countries", *Renewable and Sustainable Energy Reviews* 44, 257-270.

[69] King C. W., Maxwell J. P., Donovan A., 2015, "Comparing world economic and net energy metrics, Part 2: expenditures perspective", *Energies* 8,12975-12996.

[70] Kocaaslan O. K., 2013, "The causal link between energy and output growth:evidence from Markov switching Granger causality", *Energy Policy* 63, 1196-1206.

[71] Kraft J., Kraft A.,1978, "On the relation between energy and GNP", *Journal of Energy and Development* 3, 401-403.

[72] Kumar S., Russell R., 2002, "Technological change, technological catch-up, and capital deepening: relative contributions to growth and convergence", *American Economic Review* 92(3), 527-548.

[73] Kummel R., 2011, "The Second Law of Economics: Energy, Entropy, and the Origins of Wealth", *Springer*New York.

[74] Kwiatkowski D., Phillips P. C. B., Schmidt P., Shin, Y., 1992, "Testing the null hypothesis of stationarity against the alternative of a unit root", *Journal of Econometrics* 54 (1-3), 159-178.

[75] Lambert J. G., Hall C. A. S., Balogh S., Gupta A., Arnold M., 2014, "Energy, EROI and quality of life", *Energy Policy* 64, 153-167.

[76] Lardic S., Mignon V., 2008, "Oil prices and economic activity: an asymmetric co-integration approach", *Energy Economics* 30(3), 847-855.

[77] Lee C.-C., 2005, "Energy consumption and GDP in developing countries: A cointegrated panel analysis", *Energy Economics* 27, 340-353.

[78] Le Kama A. A., Schubert K., 2004, "Growth, Environment and Uncertain Future Preferences", *Environmental and Resource Economics* 28, 31-53.

[79] Lin E. Y.-Y., Chen P.-Y., Chen C.-C.,"Measuring green productivity of country: A generalized metafrontier Malmquist productivity index approach", *Energy* 55, 481-488.

[80] Liu Y., 2009, "Exploring the relationship between urbanization and energy consumption in China using ARDL (autoregressive distributed lag) and FDM (factor decomposition model)", *Energy* 34(11), 1846-1854.

[81] Lucas R. E., 1988, "On the mechanics of economic development", *Journal of Monetary Economics* 22, 3-42.

[82] Maji I. K., 2015 "Does clean energy contribute to economic growth? Evidence from Nigeria", *Energy Reports* 1, 145-150.

[83] Menegaki A. N., 2014, "On energy consumption and GDP studies; A meta-analysis of the last two decades", *Renewable and Sustainable Energy Reviews* 29, 31-36.

[84] Menyah K., Wolde-Rufael Y., 2010, "Energy consumption, pollutant emissions and economic growth in South Africa", *Energy Economics* 32(6), 1374-1382.

[85] Murphy D. J., Hall C. A. S., Dale M., Cleveland C. J., 2011, "Order from chaos: a preliminary protocol for determining the EROI of fuels", *Sustainability* 3, 1888-1907.

[86] Narayan P., Smyth R., 2014, "Applied econometrics and a decade of energy economics research", *Monash University Discussion Paper* ISSN 1441-5429.

[87] Odhiambo N. M., 2009, "Electricity consumption and economic growth in South Africa: a trivariate causality test", *Energy Economics* 31(5), 635-640.

[88] Odum H. T., 1973, "Energy, ecology, and economics", *AMBIO* 2(6),220227.

[89] Omri A., 2014, "An international literature survey on energy-economic growth nexus: evidence from country-specific studies", *Renewable and Sustainable Energy Reviews* 38, 951-959.

[90] Ott I., Soretz S., 2016, "Green Attitude and Economic Growth", *Environmental and Resource Economics* forthcoming.

[91] Ozcan B., Ari A., 2015, "Nuclear Energy Consumption-economic Growth Nexus in OECD: A Bootstrap Causality Test", *Procedia Economics and Finance* 30, 586-597.

[92] Ozturk I., 2010, "A literature survey on energy-growth nexus", *Energy Policy* 38, 340-349.

[93] Pablo-Romero M. D. P., Sanchez-Braza A., 2017, "Residential energy environmental Kuznets curve in the EU-28", *Energy* 125, 44-54.

[94] Pasimeni F., Pasimeni P., 2016, "An Institutional Analysis of the Europe 2020 Strategy", *Social Indicators Research* 127, 1021-1038.

[95] Payne J. E., 2010, "A survey of the electricity consumption-growth literature", *Applied Energy* 87, 723-731.

[96] Pesaran M., Shin Y., Smith R., 2001, "Bounds testing approaches to the analysis of level relationships", *Jounral of Applied Econometrics* 16 (3), 289-326.

[97] Phillips P., Perron P., 1988. "Testing for a unit root in time series regression", *Biometrika* 75 (2), 335-346.

[98] Quah D., 1993, "Galton's fallacy and tests of the convergence hypothesis", *Scandinavian Journal of Economics* 95(4), 427-443.

[99] Quah D., 1996, "Twin peaks: growth and convergence in models of distribution dynamics", *Economic Journal* 106(437), 1045-1055.

[100] Quah D., 1997, "Empirics for growth and distribution: stratification, polarization, and convergence clubs", *Journal of Economic Growth* 2(1), 27-59.

[101] Rajbhandari A., Zhang F., 2018, "Does energy efficiency promote economic growth? Evidence from a multicountry and multisectoral panel dataset", *Energy Economics* 69, 128-139.

[102] Rappai G., 2016, "Europe En Route to 2020: A New Way of Evaluating the Overall Fulfillment of the Europe 2020 Strategic Goals", *Social Indicators Research* 129, 77-93.

[103] Ricci F., 2007, "Environmental policy and growth when inputs are differentiated in pollution intensity", *Environmental and Resource Economics* 38, 285-310.

[104] Romer P. M., 1990, "Human capital and growth: theory and evidence", *Carnegie-Rochester Conference Series on Public Policy* 32, 251-286.

[105] Schou P., 2000, "Polluting Non-Renewable Resources and Growth", *Environmental and Resource Economics* 16, 211-222.

[106] Silverman B. W., 1981, “Using Kernel Density Estimates to Investigate Multimodality”, *Journal of the Royal Statistical Society* Series B 43, 97-99.

[107] Sims C. A., 1972, “Money, income, and causality”, *American Economic Review* 62 (4), 540-552.

[108] Simsek H. A., Simsek N., 2013, “Recent incentives for renewable energy in Turkey”, *Energy Policy* 63, 52-530.

[109] Solarin S. A., 2014, “Multivariate causality test of electricity consumption, capital formation, export, urbanisation and economic growth for Togo”, *Energy Study Review* 21(1).

[110] Solow R. M., 1956, “A Contribution to the Theory of Economic Growth”, *Quarterly Journal of Economics* 70(1), 65-94.

[111] Stern D. I., 1993, “Energy use and economic growth in the USA, a multivariate approach”, *Annals of the New York Academy of Sciences* 15, 137-150.

[112] Stern D. I., 2000, “A multivariate cointegration analysis of the role of energy in the US macroeconomy”, *Annals of the New York Academy of Sciences* 22, 267-283.

[113] Stern D. I., 2011, “The role of energy in economic growth”, *Annals of the New York Academy of Sciences* 1219, 25-51.

[114] Tiba S., Omri A., 2017, “Literature survey on the relationships between energy, environment and economic growth”, *Renewable and Sustainable Energy Reviews* 69, 1129-1146.

[115] Toda H. Y., Yamamoto T., 1995, “Statistical inference in vector autoregressions with possibly integrated processes”, *Journal of Econometrics* 66(1), 225-250.

[116] Walheer B., 2016a, “A multi-sector nonparametric production-frontier analysis of the economic growth and the convergence of the European countries”, *Pacific Economic Review* 21(4), 498-524.

[117] Walheer B., 2016b, “Growth and Convergence of the OECD countries: A Multi-Sector Production-Frontier Approach”, *European Journal of Operational Research* 252(2), 665-675.

[118] Walheer B., 2017, “Decomposing the Europe 2020 index”, *Social Indicators Research* doi.org/10.1007/s11205-017-1797-8

[119] Walheer B., 2018a, “Aggregation of metafrontier technology gap ratios: the case of European sectors in 1995-2015”, *European Journal of Operational Research* doi.org/10.1016/j.ejor.2018.02.048

[120] Walheer B., 2018b, “Scale efficiency for multi-output cost minimizing producers: the case of the US electricity plants”, *Energy Economics* 70, 26-36.

[121] Walheer B., 2018c, Scale, congestion, and technical efficiency of European countries: a sector-based nonparametric approach”, *Empirical Economics* accepted.

[122] Wandji Y. D. F., 2013, “Energy consumption and economic growth: evidence from Cameroon”, *Energy Policy* 61, 1295-1304.

[123] Wang K., Feng C., 2015, “Sources of production inefficiency and productivity growth in China: A global data envelopment analysis”, *Energy Economics* 49, 380-389.

[124] Wang K., Lu B., Wei Y.-M., 2013, “China’s regional energy and environmental efficiency: a range-adjusted measure based analysis”, *Applied Energy* 112, 1403-1415.

[125] Wesseh Jr P.K., Zoumara B., 2012, “Causal independence between energy consumption and economic growth in Liberia”, *Energy Policy* 50, 518-527.

[126] Zhang X.-P., Cheng X-M., Yuan J.-H., Gao X.-J., 2011, “Total-factor energy efficiency in developing countries”, *Energy Policy* 39, 644-650.

[127] Zhao Y., Wang S., 2015, “The Relationship between Urbanization, Economic Growth and Energy Consumption in China: An Econometric Perspective Analysis”, *Sustainability* 7, 5609-5627.

Appendix

Figure 7: Greenhouse gas and output per greenhouse gas emissions growths

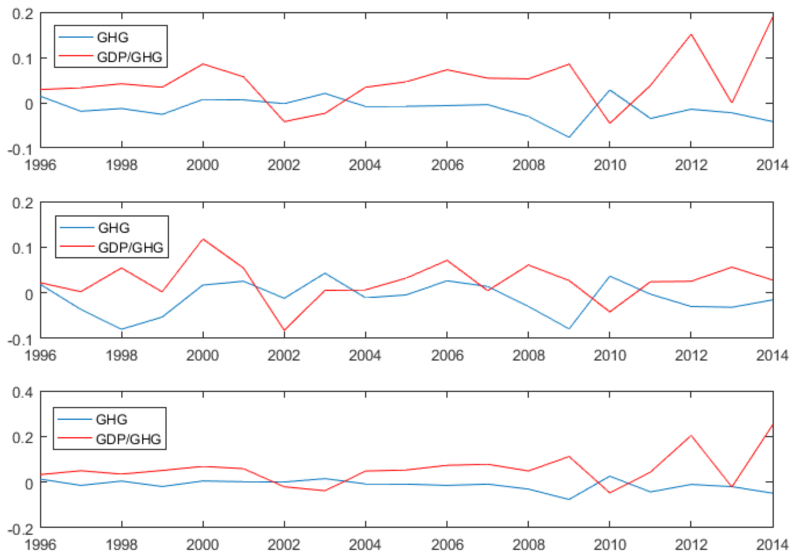


Figure 8: Energy indexes, greenhouse gas and output per greenhouse gas without Latvia

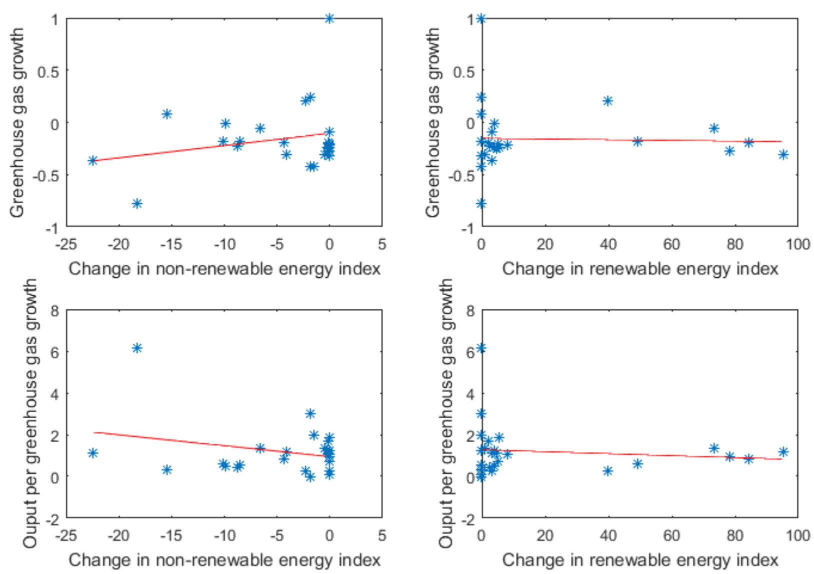


Figure 9: Renewable to non-renewable ratio growth