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Sectoral Energy- and Labour-Productivity Convergence

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Abstract. This paper empirically investigates the development of cross-country differences in energy- and labour productivity. The analysis is performed at a detailed sectoral level for 14 OECD countries, covering the period 1970–1997. A σ-convergence analysis reveals that the development over time of the cross-country variation in productivity performance differs across sectors as well as across different levels of aggregation. Both patterns of convergence as well as divergence are found. Cross-country variation of productivity levels is typically larger for energy than for labour. A β-convergence analysis provides support for the hypothesis that in most sectors lagging countries tend to catch up with technological leaders, in particular in terms of energy productivity. Moreover, the results show that convergence is conditional, meaning that productivity levels converge to country-specific steady states. Energy prices and wages are shown to positively affect energy- and labour-productivity growth, respectively. We also find evidence for the importance of economies of scale, whereas the investment share, openness and specialization play only a modest role in explaining cross-country variation in energy- and labour-productivity growth.

Key words: convergence, energy productivity, labour productivity, sectoral analysis

JEL classification: O13, O47, O5, Q43

1. Introduction

Over the last decades increasing attention is paid to the role of energy in production processes and to its importance for economic growth. Energy consumption is, however, also an important source of greenhouse gas emissions. Most governments in OECD countries explicitly recognize the need for sustainable development and aim at a decoupling of economic growth and environmental pressure. In a more operational sense, this underlines the importance of sustained growth of both labour- and energy productivity. Productivity growth is thought to be determined not only by country-specific characteristics, such as investments and factor prices, but also by developments in the outside world. Therefore, an important issue in understanding long-run productivity performance is whether the process of economic growth tends to involve reductions in productivity differences among countries, for example, due to diminishing returns to capital accumulation or technology transfers. In this paper we explore differences in energy productivity across countries and across sectors, and compare them with differences in labour productivity. Are these differences decreasing, or is the gap between leading and backward countries getting larger? Are patterns of energy-productivity similar to those of labour-productivity convergence? Do relatively inefficient countries catch-up with technological 'leaders' in a globalizing world? And if so, how quickly and by what means? We aim to answer these questions by simultaneously carrying out an empirical analysis of cross-country energy- and labour-productivity convergence at a detailed sector level, using a new dataset that merges energy data and economic data for 13 sectors and 14 OECD countries, covering the period 1970–1997.

In several respects, our paper differs from previous empirical research on cross-country productivity convergence. It extends the empirical macroeconomic convergence literature to energy-productivity developments (see also Miketa and Mulder 2005, for a complementary paper[1]). In spite of many existing cross-country studies on energy-productivity or energy-intensity developments and its determinants (for example Howarth et al. 1991; Miketa 2001; Schipper and Meyers 1992; Unander et al. 1999; Mulder and de Groot 2003a), systematic analyses of convergence from a macroeconomic perspective are rare. Hence, we add to the existing literature a systematic comparison of energy- and labour-productivity convergence, whereby the latter mainly serves as a point of reference for our analysis of energy-productivity convergence. Furthermore, we do so at a detailed sectoral level. By looking at cross-country convergence patterns *within* sectors, our analysis differs from virtually all convergence studies in the empirical growth literature, since they employ aggregate data. Important exceptions are sectoral studies by Dollar and Wolff (1988, 1993) and Bernard and Jones (1996a, b) who – using (partly) the same data source as we do (OECD's ISDB) – conclude that a convergence analysis of aggregate productivity levels masks substantial differences at the sectoral level. An important underlying reason for this result is that productivity levels, measured as the ratio of value added over a unit of input (viz. energy and labour), can substantially differ among sectors because some activities require inherently more capital, higher labour skills and/or technology than others. Aggregate productivity trends are therefore not directly attributable to technological change in individual sectors, as they can also be the result of changes in the distribution of production factors among sectors. Our sectoral approach corrects for most of the impact of such changes in the structure of production on aggregate productivity developments and, hence, establishes a closer link to issues concerning international convergence of technology driven productivity performance. Our analysis differs from the previously mentioned sectoral convergence analyses in comparing labour- and energy-productivity convergence, in further disaggregating the manufacturing sector into 10 sub-sectors,[2] in using more recent data and in carrying out a more extensive search for country- and sector-specific factors to explain productivity convergence patterns.

The paper proceeds as follows. Section 2 discusses the theoretical background for this paper including the different notions of convergence that are found in the literature. Section 3 describes the data used. In Section 4 we analyze the development of cross-country differences of energy- and labour-productivity levels within sectors over time. In Section 5 we use a panel-data approach to test the proposition that sectoral growth rates of energy- and labour productivity are inversely related to their initial levels of energy- and labour productivity, indicating possible patterns of catching-up. In addition, we try to identify the country- and sector specific fundamentals determining (differences in) energy- and labour productivity developments. Section 6 summarises and concludes.

2. Theoretical Background

The concept of productivity convergence has its roots in neoclassical growth theory, with its central notion of a transitional growth path to a steady state. The evolution of the literature on economic growth and productivity developments has resulted in a broad consensus on which are the key factors driving productivity growth across countries, and thus determining patterns of convergence and divergence. To structure a brief discussion of this issue and illuminate the various factors and mechanisms that may affect cross-country energy- and labour-productivity differences, let us take a neoclassical Cobb-Douglas production function:

$$Y = AK^{\alpha}L^{\beta}E^{1-\alpha-\beta} \tag{1}$$

where Y is output, A is technology, K is capital, L is labour and E is energy. Assuming that each input is paid according to its marginal product, Equation (1) can be rewritten in terms of average energy- and labour-productivity as follows:

$$\frac{Y}{E} = A\left(\frac{K}{E}\right)^{\alpha}\left(\frac{L}{E}\right)^{\beta} = A\left(\frac{\alpha p_E}{(1-\alpha-\beta)r}\right)^{\alpha}\left(\frac{\beta p_E}{(1-\alpha-\beta)w}\right)^{\beta} \tag{2a}$$

$$\frac{Y}{L} = A\left(\frac{K}{E}\right)^{\alpha}\left(\frac{L}{E}\right)^{\beta-1} = A\left(\frac{\alpha p_E}{(1-\alpha-\beta)r}\right)^{\alpha}\left(\frac{\beta p_E}{(1-\alpha-\beta)w}\right)^{\beta-1} \tag{2b}$$

with r, w and p_E representing, respectively, the rental price of capital, the wage rate and the energy price. From these equations it can be easily seen that cross-country differences in energy- and labour-productivity may arise from differences in factor input ratios, (relative) factor prices and the level of technological development. Concerning the dynamics, these differences may change over time as the result of factor accumulation, factor price changes and technological change, which in turn can be facilitated by processes such as trade, foreign direct investment (FDI), learning and market conditions. Thus, these phenomena are among the key factors causing cross-country productivity differences to change over time, leading to patterns of convergence or divergence.

Returning to neoclassical growth theory, the Solow-Swan model (Solow 1956; Swan 1956) postulates convergence of per capita income, driven by the assumption of diminishing returns to capital accumulation at the economy-wide level. The dynamics of the model imply that initial differences in per capita income and capital endowments vanish in the long run. In the steady state, diminishing returns are offset by technological progress, the principal source of long-run economic growth. The new or endogenous growth theory (Lucas 1988; Romer 1986, 1990) yields a more diverse picture concerning patterns of convergence. It builds on the notion that capital should be considered as a broad concept, including human and intangible capital. In this theory, economic growth is driven by accumulation of knowledge or human capital, which is (at least partially) a public good. Hence, cross-country convergence depends on the extent of international knowledge spill-overs, allowing less productive countries to catch-up with more advanced economies. As such, endogenous growth theory supports the old hypothesis of the existence of an 'advantage of backwardness' (Gerschenkron 1952), suggesting that being backward in productivity carries a potential for rapid advance (see, e.g., Abramovitz 1986). At the same time, endogenous growth theory suggests that growth differentials may persist or even increase: learning effects, externalities and market imperfections allow for economy-wide increasing returns to capital accumulation and the existence of multiple steady-states. Moreover, there is some reason to believe that technology diffusion and knowledge spillovers are local rather than global (see, for example, Keller 2002) which raises the possibility that convergence patterns depend on the spatial dimension of technological progression.

A mixed view on convergence patterns also emerges if one takes into account the role of international trade and FDI. Trade and FDI could enhance cross-country convergence through knowledge diffusion and thus diminishing cross-country differences in technology level, and through convergence in factor prices via increasing international competition. On the other hand, trade and FDI could contribute to cross-country divergence by stimulating differential factor accumulation across countries, for example, because trade advances international specialization (Grossman and Helpman 1991). These various approaches generated some degree of controversy around the issue of convergence and caused the convergence hypothesis to be the subject of extensive empirical research.[3] In this paper we do not go further into this debate, but focus instead on the cross-country differences in energy productivity, whereas the empirical convergence literature focuses on convergence of per capita income, labour productivity and total factor productivity.

Our focus on the development of cross-country energy-productivity requires some additional discussion on the driving forces behind the evolution of differences in energy productivity across countries. In a recently developed augmented version of the Solow model including pollution (emissions) as a joint product of output as well as technological progress in abatement, Brock and Taylor (2004) show that one can expect cross-country convergence of emissions per capita as nations get richer. They argue this to be in line with the empirical evidence on the existence of an Environmental Kuznets Curve. This pattern of emission intensity convergence is caused by the joint forces of output convergence and technology catch-up, possibly enhanced by sectoral shifts away from heavy industry as well as reduced cross-country heterogeneity (for example in terms of population growth and savings rates). But, contrary to emissions, energy is an intermediate input into the production process rather than a joint product of output. This implies that unless energy is strongly complementary to capital, there is not much reason to believe that diminishing returns to capital (in some augmented version of the Solow model including energy) are an important source of energy-productivity convergence across countries.[4] However, from classical as well as recent empirical research, it is well known that technological change, prices and changes in economic structure (sectoral shifts) are key determinants of aggregate energy-productivity growth (see, for example, Berndt 1978; Jorgenson 1984; Schipper and Meyers 1992).

As noted above, knowledge spillovers and international technology diffusion – possibly facilitated by (increasing) international trade and FDI – may lead to processes of technology catch-up which in turn can be a potentially important source of energy-productivity convergence. In any case, since productivity growth is primarily driven by technological change, the evidence of conditional convergence reported in this paper suggests that patterns of international energy-saving technology flows exist, while at the same time they seem to be limited and at least to some extent sector-specific. Obviously, decreasing cross-county differences in energy taxation affect energy productivity through the (relative) final prices of the input factor energy, and depend, among others, on (cross-country differences in) government policies, institutions, openness, trade and market conditions.

The role of (differences in) economic structure on aggregate energy productivity growth can be easily seen if we decompose the ratio of output to energy according to:

$$\frac{Y}{E} = \sum_{s=1}^{S} \frac{Y_s}{E_s} \frac{E_s}{E_T} \tag{3}$$

with s denoting the sectors of the economy, S indicating the total number of all sectors considered and E_T representing total final energy consumption. So, Equation (3) says that aggregate energy productivity is the sum of the energy productivity of each sub-sector (the first term on the RHS) multiplied by the energy share of each sub-sector (the second term on the RHS). The first term on the RHS is sometimes referred to as the structural effect, and indicates the effect of changes in the structure of production on aggregate productivity growth. With shifts away from (heavy) industry to services as countries get richer, the resulting decreasing cross-country heterogeneity in the economy's structure may lead to decreasing cross-country differences in aggregate energy productivity. Of course, a similar argument applies to labour productivity. Finally, several authors have stressed the fact that changes in energy mix are an important source of aggregate energy productivity developments, because some energy types (such as natural gas and electricity) are more efficient than others (such as coal and oil) in terms of available energy (see, for example, Berndt 1978; Cleveland et al. 2000; Kaufmann 2004). This can be illustrated with Equation (3), if we assume s now to represent various energy types and S the total number of different energy types used in the economy, with E_T representing total final energy consumption (expressed in a uniform unit such as ktoe). Then aggregate energy productivity is the product of the relative efficiency of the different energy types used (the first term on the RHS) and the relative shares of these different energy types (the second term on the RHS). Hence a decreasing cross-country heterogeneity in the use of various energy types is expected to contribute to cross-country convergence of aggregate energy productivity.[5]

Apart from the factors that may give rise to energy-productivity convergence, it is important to assess whether countries converge to a global or a local steady state. To address this question, the concept of conditional as opposed to unconditional convergence has been developed in the literature on convergence. The former concept posits that countries all converge to their own steady state whereas the latter assumes the existence of one steady state that is common to all countries. The empirical growth literature has found strong support for the notion of conditional convergence or club convergence (see, for example, Durlauf and Johnson 1992, Chatterji 1992, and Quah 1997 for seminal contributions). From this literature it follows that convergence can be understood in terms of levels and growth rates, which translates into a distinction between so-called σ-convergence and β-convergence (for example, Barro 1991, Barro and Sala-i-Martin 1992). The former refers to a decreasing variation of cross-country differences in productivity levels, while the latter suggests a tendency of countries with relatively low initial productivity levels to grow relatively fast, building upon the proposition that growth rates tend to decline as countries approach their steady state.[6] In this paper we will explore both patterns of σ-convergence and β-convergence. Moreover, we test whether energy- and labour productivity convergence is conditional or unconditional and which are the factors explaining (cross-country differences in) labour- and energy productivity growth.

3. Data

The analysis presented in this paper is based on a newly constructed database that merges energy data from the Energy Balances as they are published by the International Energy Agency (IEA), and economic data from the International Sectoral Database (ISDB) and the Structural Analysis Database (STAN), both published by the OECD.[7] The main idea behind the construction of this database is to establish a link between economic and energy data at a detailed sectoral level. This results in the sector classification as described in Table I.

The database covers the period 1970–1997 and includes the following countries: Australia, Belgium, Canada, Denmark, Finland, France, West-Germany, Italy, Japan, the Netherlands, Norway, Sweden, United Kingdom and the United States.

We measure energy productivity by gross value added per unit of final energy consumption and labour productivity by gross value added per worker (in full time equivalents). Value added is the net economic output of a sector, measured by the price differential between the price of output and the cost of input and comprises compensation to employees, operating surplus, the consumption of fixed capital and the excess of indirect taxes over subsidies (OECD 1998). Following the IEA, energy use is defined as final energy consumption in kilo tonnes of oil equivalence (ktoe), with sectoral data excluding transformation losses. Total employment is measured in the full-time equivalent number of persons, including self-employed.

Moreover, the database includes data on Investment, Energy Prices, Compensation of Employees, Export and Import – all at the sectoral level. The sector-specific energy prices are constructed by dividing sector-specific expenditures on energy over total sectoral energy consumption. The sector-specific expenditures are calculated as the product of the sectoral consumption of the four main energy carriers (Coal, Natural Gas, Electricity, Oil) – available from the Energy Balances – and the (annual) price of each energy

Table I. Sector Classification

	Sector	Abbreviation	ISIC Rev. 2 code
1	Food and Tobacco	FOD	31
2	Textiles and Leather	TEX	32
3	Wood and Wood Products	WOD	331[a]
4	Paper, Pulp and Printing	PAP	34
5	Chemicals	CHE	351 + 352[b]
6	Non-Metallic Minerals	NMM	36
7	Iron and Steel	IAS	371
8	Non-Ferrous Metals	NFM	372
9	Machinery	MAC	381 + 382 + 383[c]
10	Transport Equipment	MTR	384
11	Construction	CST	50
12	Services	SRV	61 + 62 + 63 + 72 + 81 + 82 + 83 + 90[d]
13	Transport	TAS	71
14	Agriculture	AGR	10

[a]WOD excludes furniture since the sector WOD in the IEA Energy Balances excludes furniture.
[b]CHE includes non-energetic energy consumption, i.e. using energy carriers as feedstock.
[c]MAC = Metal Products (BMA, 381) + Agricultural and Industrial Machinery (MAI, 382) + Electrical Goods (MEL, 383).
[d]SRV = Wholesale and retail trade, restaurants and hotels (RET) + Communication (COM) + Finance, insurance, real estate and business services (FNI) + Community, social and personal services (SOC).

carrier at the aggregate industrial sector – available from the IEA Energy Prices and Taxes series. In addition, some missing aggregate energy price data series have been constructed (see the Annex to this paper for details). Detailed descriptive statistics per sector and per country covering the growth rate of energy- and labour productivity, the log-levels of energy- and labour productivity and of GDP, and the levels of wages, energy prices, investment shares, openness, the Balassa indices and sector shares can be found in the Annex to this paper. The latter four variables are introduced and discussed in Section 5.2.

All currency-denominated variables are in 1990 US$ and have been converted by the OECD using 1990 purchasing power parities (PPPs). In principle, the theoretically most appropriate conversion factors for productivity comparisons at the sectoral level are to be based on a comparison of output prices by industry of origin, rather than on expenditure prices (see, for example, van Ark and Pilat 1993). Expenditure PPPs exclude the part of output that is exported, while they include imported goods produced elsewhere; they take account of differences in trade and transport margins and indirect taxes between countries, and they do not cover intermediate products. The main problem in using the production or industry-of-origin approach, however, is the limited availability of producer-price based PPPs, in particular for non-Manufacturing sectors (van Ark 1993). Moreover, we have no a priori reason to presume that the drawbacks of expenditure PPPs differ substantially across countries. Hence, we follow most studies in using expenditure PPPs. This enables us to do a systematic cross-country convergence analysis of energy- and labour-productivity performance at a high level of sectoral detail. Obviously, the results presented in this paper should be interpreted with caution, bearing in mind the before mentioned issue (see Sørensen 2001, and Bernard and Jones 2001 for a discussion).

4. σ-Convergence

This section deals with the notion of convergence in terms of levels. Do cross-country differences in energy- and labour-productivity levels decrease over time? Are patterns of energy-productivity convergence similar to those of labour-productivity convergence? And to what extent do the results depend on the level of aggregation? To answer these questions we calculated for each (sub-)sector – based on a balanced sample of 14 OECD countries (insofar as data are available) – the yearly unweighted cross-country standard deviation (σ) of the log of energy- and labour productivity.[8] Table II shows the results for the years 1976 and 1990. Results for the entire time span for which data are available are graphically presented in the Annex to this paper. None of the results described in the remainder are peculiar to the choice of the two years for which the standard deviation is presented in Table II.

The macroeconomic development of the standard deviation of the log of 'energy- and labour-productivity levels (with 'macroeconomic' referring to the sum of aggregate Manufacturing, Transport, Services and Agriculture) reveals that cross-country differences in energy-productivity levels are substantially larger than cross-country differences of labour-productivity levels. Moreover, it can be seen that over time the standard deviation of the log of energy-productivity performance is increasing, indicating σ-divergence, while the opposite is true for cross-country labour-productivity performance, displaying a pattern of σ-convergence.

As we noted in the introduction, a convergence analysis at aggregate levels may mask considerable variation in sectoral productivity developments (cf. Bernard and Jones 1996a, b; Dollar and Wolff 1988, 1993). Therefore, we continue by examining the development of cross-country productivity differentials within different sectors, viz. (aggregate) Manufacturing, Transport, Services and Agriculture. It can clearly be seen that only Manufacturing resembles the macroeconomic pattern of σ-divergence for energy productivity. Transport, Agriculture, and, in particular, Services, display evidence of σ-convergence. Note that the cross-country variation is relatively high in

Table II. Standard deviation of log of energy-and labour productivity, 1976 and 1990

	Energy productivity		Labour productivity	
	1976	1990	1976	1990
Macroeconomic level [a]	0.261	0.294	0.210	0.171
Main sectors				
Manufacturing[b]	0.444	0.512	0.212	0.204
Services[c]	0.839	0.605	0.220	0.172
Transport[d]	0.510	0.439	0.278	0.248
Agriculture[b]	0.492	0.320	0.305	0.256
Manufacturing sectors				
Chemicals[g]	0.519	0.557	0.366	0.265
Food and Tobacco[i]	0.546	0.436	0.267	0.258
Iron and Steel[e]	0.468	0.580	0.481	0.278
Machinery[h]	0.570	0.350	0.202	0.239
Transport Equipment[i]	0.473	0.401	0.248	0.241
Non-Ferrous Metals[f]	0.473	0.660	0.426	0.313
Non-Metallic Minerals[g]	0.467	0.269	0.226	0.187
Paper, Pulp and Printing[e]	0.934	0.950	0.252	0.176
Textiles and Leather[i]	0.359	0.300	0.203	0.190
Wood and Wood Products[j]	0.887	0.848	0.362	0.225

[a]Excludes Canada, Japan, The Netherlands and Sweden due to limited data availability.
[b]Excludes Japan and The Netherlands due to limited data availability.
[c]Excludes The Netherlands and Sweden due to limited data availability.
[d]Excludes Canada and The Netherlands due to limited data availability.
[e]Excludes Australia and Japan due to limited data availability.
[f]Excludes Australia and Denmark due to limited data availability.
[g]Excludes Australia due to limited data availability.
[h]Excludes Australia, Canada, Japan and The Netherlands due to limited data availability.
[i]Excludes Australia and Canada due to limited data availability.
[j]Excludes Australia, Canada, France, Japan, United Kingdom and USA due to limited data availability.

Services, which is to a large extent due to the exceptional and so far unexplained energy-productivity performance of Finland and Italy.[9] The macroeconomic pattern of σ-convergence for labour productivity is only evident in Services and to a lesser extent in the Agricultural sector. Variation in cross-country productivity differentials remains overall fairly constant within aggregate Manufacturing and Transport. Comparing the results for energy and labour productivity reveals again that in each sector the cross-country variation of energy productivity is substantially larger than of labour productivity. They accord well with the findings of Bernard and Jones (1996a), who by means of a conclusion suggest "that international flows, associated mostly with Manufacturing, may not be contributing substantially to convergence either through capital accumulation or technological transfer" (Bernard and Jones 1996a:1230). Our analysis suggests that this conclusion holds even stronger for manufacturing energy-productivity performance, where international flows cannot prevent an increase in cross-country differences of productivity levels.

The previous results raise the question as to what determines these cross-country productivity differences. In our search for an answer we subsequently take three steps. First, we go one step further in the σ-convergence analysis than Bernard and Jones (1996a, b) by examining productivity convergence for a breakdown of aggregate Manufacturing in order to see to whether the energy-productivity divergence and the lack of labour-productivity convergence observed in aggregate Manufacturing is also found within the different Manufacturing sub-sectors. Second, we perform a β-convergence analysis to test whether a statistically significant negative relationship exists between the initial level and the growth rate of productivity, in order to gain a better insight in the mechanism behind the observed convergence patterns. Third, we will try to explain differences in cross-country productivity growth by examining the role of different country-specific variables in driving energy- and labour-productivity growth at the sectoral level. The remaining part of this section is devoted to a σ-convergence analysis for a breakdown of aggregate Manufacturing into 10 sub-sectors. The other issues are the subject of Section 5.

The lower part of Table II presents the standard deviation of the log of, respectively, energy- and labour productivity for each of the 10 Manufacturing sub-sectors included in our dataset. The results reveal that the pattern of divergence in cross-country energy-productivity performance at the level of aggregate Manufacturing is to be found only in Iron and Steel and Non-Ferrous Metals. On the contrary, Food, Machinery, Non-metallic Minerals and Textiles all display evidence of (strong) σ-convergence. Cross-country productivity differences remain more or less constant in Chemicals, Transport Equipment, Paper and Wood. It can also be seen that the lack of labour-productivity convergence in aggregate Manufacturing is the result of mixed convergence patterns in different manufacturing sectors. Chemicals, Iron and Steel, Non-ferrous Metals and Wood exhibit (strong) convergence, while Machinery shows the opposite pattern of divergence. The sectors Food, Non-Metallic Minerals, Textile, Paper and Transport Equipment display no clear evidence for either convergence or divergence.

In conclusion, cross-country variation of energy-productivity is substantially higher than of labour-productivity at all levels of sectoral aggregation, and in particular in Services, Chemicals, Paper, Wood and at an ever increasing rate also in Iron and Steel and Non-Ferrous Metals. In Machinery, however, energy- and labour-productivity have strongly converged, resulting in a relatively small – although seemingly persistent – difference in the degree of cross-country variance. Moreover, convergence patterns turned out to depend on the level of aggregation, with different sectors displaying varying behaviour: some show reduction in variation, some increasing variation and others neither a clear reduction or increase in cross-country differences.

These results suggest that different mechanisms may be at work in the different sectors. For example, the observed patterns of divergence might be the result of increasing international specialization while the tendency to converge might be caused by technology spill-overs from 'leaders' to 'followers', allowing lagging countries to catch-up. Moreover, our results suggest that determinants of energy-productivity growth and labour-productivity growth might differ from each other, since we found no clear-cut (and sometimes even an opposite) relationship between cross-country convergence patterns in terms of energy productivity and labour productivity. Finally, even in those sectors showing evidence of convergence there remain substantial cross-country productivity differences, in particular in terms of energy productivity.

A possible explanation for the relatively high variation in energy-productivity levels across countries might be that cross-country differences in environmental awareness (influenced by social pressure) or stringency of environmental policies cause energy-efficiency improvements to be a matter of urgency at different degrees in different countries. Another reason might be a lack of international diffusion of energy-saving technologies as compared to technologies enhancing labour productivity. This can be caused by the fact that, in contrast with labour costs, in most sectors energy costs form only a small part of total production costs and, hence, firms do not have the incentive to search for best-practice technologies at the international market, as opposed to labour-augmenting technologies. Another explanation for the relatively high cross-country variation in energy-productivity levels might be the heterogeneity in energy mix across the OECD countries.

In any case, the observed cross-country variation in energy-productivity levels suggests that convergence does not pertain to a uniform steady state for all countries. In order to further examine this issue, we continue in the next section with a search for empirical regularities in the productivity improvements over our cross-section of countries by testing for sectoral patterns of β-convergence. As part of that analysis we will also try to explain (differences in) energy- and labour-productivity growth.

5. β-Convergence

The concept of β-convergence builds on the notion that countries that are further away from their steady-state level experience faster productivity growth. An empirical test thus builds on a regression of productivity growth on initial productivity. A negative correlation between the two provides an indication for convergence, because it suggests that countries with relatively low initial energy- and labour-productivity levels catch-up to more advanced economies (see Section 2). A problem that one encounters in this respect is the quantitative characterization of the steady-state productivity level. Several approaches can be followed, each making different assumptions regarding the role of country-specific characteristics in driving productivity growth across countries. In this paper, we show the results for two types of analysis. First, we do a conditional convergence analysis, assuming productivity levels to converge towards multiple steady states that are conditional on (unspecified) country-specific characteristics.[10] Second, we try to identify the country-specific characteristics that determine (differences in) energy- and labour-productivity growth across countries.

Econometrically, we have estimated four different types of models, viz. a pooled Ordinary Least Squares model, a fixed-effects model, a random-effects model and a random-effects model with a Mundlak specification. On theoretical as well as on econometric ground, there are good reasons to prefer the fixed-effects model. The OLS estimation method is valid only under the assumption that the error term is independent of the explanatory variables. However, in the growth regressions that we will estimate it is very likely that the error term contains all sorts of (unobserved) country-specific tangible and intangible factors that affect productivity growth.[11] As a result, OLS estimates tend to be biased and inconsistent in this case (Hsiao 1986). A panel approach applying fixed- or random-effects models can be used to solve this problem. This approach is capable of allowing for cross-country differences in steady states in the form of unobservable individual 'country-effects', thus diminishing the omitted-variables problem (Islam 1995). Comparing the fixed- and the random-effects model, the random-effects model uses up fewer degrees of freedom than the fixed-effects model and is conceptually appealing because of its characterization of the sources of the errors in a dataset with cross-section and time-series variation. However, in a growth context the requirement in a random-effects model of zero correlation between the individual country-effects and the observed explanatory variables is problematic, implying it to be an inadequate formulation in the context of our study. This problem can be solved by explicitly specifying the individual country-effects as a function of the variables with which it is supposedly correlated. This can be done by following the specification suggested by Mundlak (1978).[12]

In conclusion, there is reason to believe that the fixed-effects model or the random-effects model with Mundlak adjustment are to be preferred over the pooled OLS regression model and the normal random-effects model. For reasons of space constraints, in the remainder of this section we only report the results of the fixed-effects models, using the Least Squares Dummy Variables (LSDV) estimator. All other results for the four types of models that we have estimated – including specification tests that in almost all cases point at the fixed-effects model as the model to be preferred – can be found in the Annex to this paper. In Section 5.1 we report the results for the model in which the country-characteristics are not specified, viz. purely modelled as fixed effects. In Section 5.2 we go one step further and try to identify the country-specific characteristics that determine differences in energy- and labour-productivity growth across countries.

5.1. SECTORAL PATTERNS OF β-CONVERGENCE

As was just explained, we start our analysis of β-convergence by implementing a fixed-effects panel-data model for each sector, regressing the growth rate (g) of, respectively, energy- and labour productivity (y), on the log of its initial level (y_{t-1}) and unspecified country-specific (fixed) effects (α_i):

$$g_{it} = \alpha_i + \beta \ln(y)_{i,t-1} + \varepsilon_{it} \tag{4}$$

with i and t denoting, respectively, the cross-country and the time-series dimension. We assume ε_{it} to be an independently identically distributed random variable with mean 0 and variance σ_ε^2. Following Islam (1995) we use five-year time intervals in order to reduce the influence of business-cycle fluctuations and serial correlation of the error term. Hence, the growth rate (g) in Equation (4) is an average over a five-year period. Because of notational ease we use the symbol y interchangeably for energy productivity (y_E) and labour productivity (y_L). The proper interpretation will be clear from the context.

In Tables IIIa and IIIb we present for each sector the estimated coefficient β obtained from Equation (4) for energy- and labour-productivity, respectively, including various indicators and specification tests, which we will discuss below.[13] From Table IIIa it can be seen that we obtain a negative estimate of β for energy-productivity growth in all sectors, indicating the existence of β-convergence. Moreover, the estimate is statistically significant (at 1% significance level) in virtually all sectors.

Using the estimated values of β, the speed of convergence λ at which the productivity level is converging to a uniform productivity level can be calculated according to $\lambda = -[(1/T)\log(\beta + 1)]$ with T denoting the length of the time interval under consideration, viz. 5 in this application. A convenient

Table III. (a) β-convergence for energy productivity and (b) β-convergence for labour productivity

	Total	Manufac-turing	Agriculture	Services	Transport	Chemicals	Food and Tobacco	Iron and Steel	Machinery	Transport Equipment	Non-Ferrous Metals	Non-Metallic Minerals	Paper	Textiles	Wood
a. β-convergence for energy productivity															
β	-0.221^{***}	-0.616^{***}	-0.480^{***}	-0.218^{*}	-0.630^{***}	-0.262^{***}	-0.518^{***}	-0.389^{***}	−0.231	-0.950^{***}	-0.592^{***}	-0.509^{***}	-0.651^{***}	-0.861^{***}	-1.064^{***}
	(0.07)	(0.07)	(0.09)	(0.12)	(0.16)	(0.08)	(0.13)	(0.11)	(0.14)	(0.11)	(0.14)	(0.10)	(0.10)	(0.13)	(0.19)
Implied λ	0.050	0.192	0.131	0.049	0.199	0.061	0.146	0.099	0.052	0.601	0.180	0.142	0.211	0.3949	NA
F-stat	10.26	82.22	29.15	3.48	15.65	9.83	16.07	12.21	2.85	71.07	17.26	26.96	39.72	44.95	30.03
Prob > F	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00
R^2	0.41	0.76	0.61	0.44	0.42	0.33	0.36	0.32	0.31	0.68	0.38	0.55	0.60	0.60	0.60
ρ	0.65	0.88	0.45	0.28	0.88	0.51	0.78	0.56	0.16	0.77	0.73	0.42	0.93	0.62	0.98
# countries	13	14	14	9	12	13	13	13	13	13	12	13	13	13	12
# observ.	48	54	59	35	53	61	55	63	48	56	54	57	52	52	40
b. β-convergence for labour productivity															
β	-0.107^{***}	−0.055	-0.083^{*}	-0.178^{***}	−0.104	-0.093^{*}	-0.189^{***}	−0.064	−0.054	-0.295^{**}	−0.044	-0.209^{***}	−0.105	-0.233^{***}	-0.230^{***}
	(0.03)	(0.04)	(0.04)	(0.04)	(0.11)	(0.05)	(0.05)	(0.11)	(0.05)	(0.12)	(0.09)	(0.06)	(0.08)	(0.05)	(0.07)
Implied λ	0.023	0.011	0.017	0.039	0.022	0.020	0.042	0.013	0.011	0.070	0.009	0.047	0.022	0.053	0.052
F-stat	16.66	2.09	3.71	17.86	0.87	3.68	12.03	0.37	1.23	5.98	0.22	10.83	1.81	18.28	12.52
Prob > F	0.00	0.15	0.06	0.00	0.36	0.06	0.00	0.55	0.27	0.02	0.64	0.00	0.19	0.00	0.00
R^2	0.68	0.33	0.39	0.80	0.16	0.29	0.49	0.11	0.45	0.22	0.10	0.39	0.24	0.33	0.47
ρ	0.48	0.28	0.31	0.62	0.07	0.19	0.44	0.06	0.37	0.21	0.08	0.28	0.17	0.20	0.22
# countries	14	14	14	8	11	13	13	13	12	10	13	12	13	13	13
# observ.	60	68	66	32	46	63	61	63	57	42	63	57	61	61	63

Standard errors in parentheses. Asterisks denote levels of significance: *** at 1%, ** at 5%, and * at 10%. ρ indicates the fraction of variance due to the fixed error component.

way of expressing this speed of convergence is the time t needed for the energy-productivity level to move halfway its initial level (y_0) and the steady state productivity level y^*. This period of time is commonly referred to as the 'half life' (H).[14] The implied values of λ are also shown in Table IIIa.

It can be seen that the individual country effect explains between 16% (Machinery) and 98% (Wood) of the total unexplained variance, as indicated by ρ in Table IIIa. These results suggest that energy-productivity convergence depends to a large extent on individual country-effects, indicating convergence to be conditional rather than absolute in virtually all sectors. The estimated half life is between 1 year (Transport Equipment) and 14 years (Total). Of course, these results raise the question as to what are the country-specific variables that apparently are so important in driving energy-productivity growth. Before returning to this question (in Section 5.2) we will look at the results of estimating Equation (4) for labour-productivity. The results are presented in Table IIIb.

From Table IIIb it can be seen that also in terms of labour-productivity growth β is negative in all sectors. Moreover, these estimates are statistically significant in most sectors, with aggregate Manufacturing being an important exception. These results confirm the findings of Bernard and Jones (1996a) who also report strong evidence for convergence in Services, weak evidence in Agriculture and lack of labour-productivity convergence in Manufacturing. As compared to energy productivity, in most sectors the estimates of β are rather small, indicating that lagging countries catch-up only slowly. The implied values for the speed of convergence (λ) confirm the finding of a slow rate of convergence: the time needed for labour productivity to move halfway its initial level (y_0) and the steady state y^* varies from 47 years (Transport Equipment) and 77 years (Non-Ferrous Metals).

Similar to the results for energy productivity, the individual country effects explain a substantial part of the total unexplained variance, as indicated by ρ in Table IIIb. However, the evidence on conditional labour-productivity convergence is less clear-cut than it is for energy-productivity convergence. As compared to energy productivity (see Table IIIa), the individual country effects also play a smaller role in explaining total unexplained variance in all sectors, of course except for Services and Machinery. For labour productivity these percentages lie in between 6% (Iron and Steel) and 62% (Services). In conclusion, these results suggest labour productivity convergence to be also conditional rather than absolute in most sectors. The evidence on the role of country-specific characteristics is, however, more ambiguous than in the case of energy-productivity convergence. Apparently, in terms of labour productivity the variation in explanatory variables over time is relatively small as compared to cross-country differences.

As previously noted, β-convergence is a necessary but not a sufficient condition for σ-convergence. Our findings confirm that those sectors showing evidence of σ-convergence (see Section 4) also display evidence of β-convergence. However, the opposite is not necessarily true, as is illustrated for labour productivity by the sectors Machinery, Non-Metallic Minerals and Textiles: they pass the test for β-convergence without showing evidence of σ-convergence (see Table II). So, despite evidence of β-convergence, cross-country differences in productivity levels remain to exist and even increase in some sectors. Clearly, country-specific variables do play an important role in explaining these patterns, as also shown by the presented evidence of β-convergence. Recall from Section 2 that several mechanisms may be at work, causing 'followers' to grow faster than 'leaders': advanced economies may suffer from diminishing returns, lagging countries may benefit from knowledge spill-overs, production processes may converge due to increasing competition, etcetera. On the other hand, persistent differences in, for example, energy prices or wages, investment shares or specialization patterns, may contribute to persistent or even increasing productivity differences across countries. In order to explain differences in cross-country energy- and labour-productivity growth, in the next section we extend our β-convergence analysis by including relevant country-specific variables that may explain cross-country variation in energy- and labour productivity growth.

5.2. SECTORAL DETERMINANTS OF β-CONVERGENCE

We search for country-specific sectoral determinants of energy- and labour-productivity growth by including a number of country-specific explanatory variables in the various regression models. We change the fixed-effects model in Equation (4) as follows:

$$g_{it} = \alpha_i + \beta \ln(y)_{i,t-1} + \sum_{j=1}^{5} \gamma_j x^j_{it} + \varepsilon_{it} \qquad (5)$$

with x_i^j the additional country-specific explanatory variables and all other variables defined as in Equation (4). The specified explanatory variables x_i^j are defined at the sectoral level and include:

$$\text{Energy prices}: \quad x_{it}^{1E} = \frac{\left(p_{E,t} + p_{E,t-1} + p_{E,t-2}\right)}{3}$$

$$\text{Wages}: \quad x_{it}^{1L} = \frac{\left(w_t + w_{t-1} + w_{t-2}\right)}{3}$$

$$\text{Investment share :} \quad x_{it}^2 = \frac{I}{Y}$$

$$\text{Openness :} \quad x_{it}^3 = \frac{XGS + MGS}{Y}$$

$$\text{Balassa index :} \quad x_{it}^4 = \frac{XGS_i / \sum_{i=1}^{14} XGS_i}{\sum_{s=1}^{10} XGS_{i,s} / \sum_{i=1}^{14} \sum_{s=1}^{10} XGS_{i,s}}$$

$$\text{Economies of scale :} \quad x_{it}^5 = \frac{Y_S}{\sum_{s=1}^{13} Y_S}$$

where sectoral indices are omitted for reasons of expositional clarity and with energy prices (x_{it}^{1E}) or wages (x_{it}^{1L}) included, respectively, in case of explaining energy-productivity growth or labour-productivity growth.

We expect energy prices and wages to be positively correlated with, respectively, energy- and labour-productivity growth. We took a 3-year moving average for the energy price and wages to avoid capturing the effect of short-term price fluctuations, assuming that investments in energy- and labour-augmenting technologies do respond to a structural trend in energy price/wage developments rather than to short term fluctuations. By including the investment share as an explanatory variable we test for the so-called embodiment hypothesis or a vintage effect, assuming that higher investment will contribute to increasing energy- and labour-productivity growth via technological change embodied in new capital goods (see, for example, Howarth et al. 1991; Mulder et al. 2003). We expect openness to have a positive impact on productivity growth, since an open sector faces relatively strong competition as well as exchange of knowledge, both of which we assume to have a stimulating effect on productivity growth. The Balassa index is an indictor measuring relative specialization patterns. We expect that if a country specializes in a particular sector, that that sector will be technologically relatively advanced, and hence we expect a positive effect on productivity. Finally, including an indicator for the relative size of a sector within a country captures the potential effect of economies of scale on productivity growth, assuming that a large sector is able to invest relatively much in R&D and in new capital goods and, hence, might be a technological leader displaying relatively high productivity growth rates.

In Table IV we present the results of regressing average energy-productivity growth rates on initial energy productivity levels and these additional explanatory variables, according to Equation (5).[15]

From Table IV it can be seen that the estimates of β are again negative in all sectors, and that all these estimates are statistically significant as well (in most sectors at the 1% significance level). The speed of convergence measured by the half life lies now in between 1 year (Textiles) and 8 years (Machinery). Compared to the results presented in Table IIIa this means a higher speed of convergence in most sectors.

Concerning the additional explanatory variables, we find that the energy-price has the expected (positive) sign in all sectors, while the positive impact of energy prices on energy-productivity growth is statistically significant in Chemicals, Iron and Steel, Non-Metallic Minerals and Paper. This result makes sense since these are energy-intensive sectors. The effect of the investment share, openness, specialization, and economies of scale on energy-productivity growth is, however, limited and with mixed positive and negative signs. Of these variables specialization, measured by the Balassa index, and economies of scale, measured by the relative size of a sector within a country, have the largest statistically significant effect on energy-productivity growth. The Balassa index has a statistically significant positive effect in Iron and Steel and Non-Metallic Minerals, and a statistically significant negative effect in Chemicals, and Paper. The economies of scale effects is statistically significant positive in Chemicals and Non-Metallic Minerals and statistically significant negative in Transport Equipment. We find the vintage effect to have a statistically significant positive effect in the Transport sector only. We use a Likelihood Ratio test to discriminate between the restricted model of Equation (4) and the unrestricted model of Equation (5), in order to verify whether the inclusion of the additional variables does make sense at all. The test results show that for the sectors Agriculture, Food, Machinery and Transport Equipment we cannot reject the hypothesis that the coefficients on the additional variables are jointly zero. Thus, in all other sectors the model has improved by including the additional explanatory variables, but indeed only to a limited extent. Together with the fact that even after including additional explanatory variables, the individual country effect still explains between 66% (Textiles) and 97% (Services) of the total unexplained variance as shown by ρ, this suggests other country-specific factors than those currently included play an important role in driving cross-country energy-productivity growth patterns.

Table IV. Determinants of β-convergence for energy productivity

	Agriculture	Services	Transport	Chemicals	Food and Tobacco	Iron and Steel	Machinery	Transport Equipment	Non-Ferrous Metals	Non-Metalic Minerals	Paper	Textiles	Wood
β	−0.808***	−0.740***	−0.390*	−0.723***	−0.776***	−0.718***	−0.342*	−0.876**	−0.382***	−0.837***	−0.518**	−0.918***	−1.457***
	(0.14)	(−0.21)	(0.21)	(0.13)	(0.24)	(0.16)	(0.19)	(0.31)	(0.12)	(0.15)	(0.18)	(0.20)	(0.28)
Implied λ	0.330	0.269	0.099	0.257	0.299	0.253	0.0837	0.417	0.096	0.363	0.146	0.500	NA
P_E	0.095	0.910	0.054	1.235*	0.842	1.519	0.074	−0.485	0.540	−0.035	0.840*	0.742	−0.530
	(0.87)	(0.55)	(0.14)	(0.62)	(0.74)	(1.14)	(0.75)	(−0.55)	(0.76)	(1.50)	(0.43)	(0.87)	(0.42)
I/Y	−0.399	−0.9974	−0.133	0.008	−0.338	−0.583	2.806	0.789	−0.094	1.605	−0.015	0.619	−2.092**
	(0.96)	(0.83)	(0.32)	(0.35)	(1.11)	(0.60)	(1.96)	(1.36)	(0.33)	(0.94)	(0.71)	(1.48)	(0.90)
Openness				0.010	0.038	0.001	0.009	−0.025	−0.020	−0.018	0.026	−0.030	0.035
				(0.03)	(0.06)	(0.02)	(0.04)	(0.05)	(0.03)	(0.11)	(0.06)	(0.03)	(0.04)
Balassa				−0.652*	−0.334	0.305*	0.794	0.967	0.011	−0.150	−0.025	0.160	0.021
				(0.32)	(0.31)	(0.15)	(0.64)	(0.60)	(0.06)	(0.17)	(0.08)	(0.18)	(0.05)
Y_i/Y	9.436	6.545*	17.573***	53.823***	−3.206	−8.123	−1.379	−14.462	87.283	−26.782	14.965	−13.079	54.457
	(6.61)	(2.84)	(3.71)	(10.12)	(10.12)	(16.67)	(4.61)	(19.65)	(50.90)	(22.25)	(10.53)	(11.28)	(55.83)
F-stat	9.58	3.6	13.71	10.67	3	6.03	1.19	2.08	3.45	6.04	3.9	5.57	6.01
Prob > F	0.00	0.06	0.00	0.00	0.03	0.00	0.35	0.13	0.02	0.00	0.01	0.00	0.01
R^2	0.69	0.80	0.80	0.79	0.58	0.73	0.64	0.56	0.65	0.78	0.68	0.74	0.83
ρ	0.77	0.97	0.94	0.94	0.88	0.89	0.69	0.85	0.86	0.79	0.97	0.67	0.99
LR-test	3.38	9.11	28.14	35.56	8.46	9.39	7.42	7.1	10.98	11.2	11.45	5.15	14.41
Prob > χ^2	0.34	0.03	0.00	0.00	0.13	0.09	0.19	0.21	0.05	0.05	0.04	0.40	0.01
# countries	13	5	9	12	12	13	12	9	12	11	11	12	9
# observ.	46	17	31	38	37	42	38	28	39	35	33	36	24

Standard errors in parentheses. Asterisks denote levels of significance: *** at 1%, ** at 5%, and * at 10%. ρ indicates the fraction of variance due to the fixed error component.

In Table V we present the results for labour-productivity growth.[16] The results reveal (again) negative estimates of β in all sectors. The obtained estimates are all statistically significant, except for Services and Transport Equipment. The speed of convergence measured by the half life lies now in between 1 year (Non-Metallic Minerals) and 99 years (Serivces). Compared to the results presented in Table IIIb this also means a higher speed of convergence in most sectors. We find that wages have the expected (positive) sign in all sectors except for Services, while the positive impact of wages on labour-productivity growth is statistically significant in all sectors except Services, Chemicals, and Non-Ferrous Metals. Like for energy productivity, the effect of investment share, openness, specialization, and economies of scale on labour-productivity growth is limited and with mixed positive and negative signs. Of these variables, economies of scale have the largest statically significant effect on labour productivity growth, with statistically significant positive effects in Transport, Chemicals, Iron and Steel, Machinery, Paper and Wood, and a statistically significant negative effect in Services. We find the Balassa index to have a statistically significant positive effect in Non-Metallic Minerals, and a statistically significant negative effect in Food and Iron and Steel. The statistically significant effects of openness are positive in the Non-Metallic Minerals and Paper sector while negative in the sectors Chemicals and Wood. Finally, again the results do not give much support to the vintage effect, with Iron and Steel and Non-Ferrous Metals being the only sectors displaying a statistically significant positive effect, while the effect is negative in Agriculture, Food and Wood. Finally, also for labour productivity we find the individual country effect to explain a large fraction of the total unexplained variance, in spite of including a range of additional explanatory variables. However, contrary to energy-productivity growth, the results of the Likelihood Ratio test indicate that, except for Transport Equipment, we can reject the hypothesis that the coefficients on the additional variables are jointly zero. In other words, for labour-productivity, the regression model of Equation (5) is a better approximation of our data than the restricted models of Equation (4).

In conclusion, the extended β-convergence analysis presented in this section confirmed that energy- and labour-productivity convergence are conditional rather than absolute, but can only partly answer the question as to which are the country-specific determinants of productivity growth driving the observed convergence patterns. In short, higher energy prices and wages are found to stimulate, respectively, energy-productivity growth (in the energy–intensive sectors) and labour-productivity growth, while the role of specialization, economies of scale and particularly openness and investment share seems to be limited.

Table V. Determinants of β-convergence for labour productivity

	Agriculture	Services	Transport	Chemicals	Food and Tobacco	Iron and Steel	Machinery	Transport Equipment	Non-Ferrous Metals	Non-Metalic Minerals	Paper	Textiles	Wood
β	−0.281***	−0.034	−0.870***	−0.480***	−0.493***	−0.842*	−0.397***	−0.360	−0.802**	−0.913***	−0.581***	−1.042***	−0.656***
	(0.09)	(0.14)	(0.14)	(0.15)	(0.10)	(0.41)	(0.11)	(0.51)	(0.29)	(0.16)	(0.15)	(0.15)	(0.12)
Implied λ	0.066	0.007	0.408	0.131	0.136	0.369	0.101	0.089	0.324	0.488	0.174	NA	0.214
Wage	0.172***	−0.213	0.400***	0.043	0.286***	0.188	0.147***	0.182	0.169	0.363***	0.258***	0.686***	0.318***
	(0.06)	(0.12)	(0.07)	(0.07)	(0.05)	(0.12)	(0.04)	(0.23)	(0.09)	(0.07)	(0.06)	(0.11)	(0.06)
I/Y	−0.453	−0.057	−0.406	0.809	−0.443	1.490	0.072	0.094	−0.472	−0.407	−0.262	0.204	−0.777*
	(0.29)	(0.18)	(0.24)	(0.81)	(0.40)	(1.55)	(0.60)	(1.32)	(0.78)	(0.35)	(0.19)	(0.47)	(0.42)
Openness				0.004	−0.031	0.020	−0.009	0.027	0.026	0.143**	0.039	0.011	−0.010
				(0.03)	(0.02)	(0.05)	(0.02)	(0.05)	(0.03)	(0.06)	(0.03)	(0.01)	(0.03)
Balassa				−0.011	−0.175**	−0.178	−0.158	−0.924	0.035	0.316***	−0.031	0.005	−0.019
				(0.33)	(0.08)	(0.53)	(0.30)	(1.06)	(0.04)	(0.11)	(0.03)	(0.06)	(0.02)
Y_i/Y	0.164	0.700	10.971***	54.522**	0.922	−0.308	6.429**	10.085	100.344	−2.201	8.756**	−3.269	3.453
	(2.12)	(0.79)	(3.07)	(18.25)	(2.39)	(80.27)	(2.47)	(17.73)	(85.46)	(8.83)	(4.11)	(4.40)	(12.96)
F-stat	3.51	2.18	16.39	3.66	8.65	1.65	12.65	1.00	3.40	7.40	13.13	11.12	10.46
Prob > F	0.02	0.15	0.00	0.02	0.00	0.28	0.00	0.48	0.08	0.00	0.00	0.00	0.00
R^2	0.52	0.84	0.77	0.72	0.78	0.71	0.88	0.43	0.85	0.71	0.81	0.74	0.83
ρ	0.26	0.90	0.83	0.97	0.96	0.76	0.93	0.48	0.95	0.77	0.69	0.73	0.80
LR-test	15.40	5.49	46.77	24.19	41.25	9.21	52.78	9.67	16.22	32.25	60.05	45.07	38.87
Prob > χ^2	0.00	0.14	0.00	0.00	0.00	0.10	0.00	0.09	0.01	0.00	0.00	0.00	0.00
# countries	13	5	9	8	12	6	9	7	6	11	11	12	10
# observ.	56	19	37	27	48	18	35	23	18	44	44	48	39

Standard errors in parentheses. Asterisks denote levels of significance: *** at 1%, ** at 5%, and * at 10%. ρ indicates the fraction of variance due to the fixed error component.

6. Conclusions

This paper extends the existing empirical analyses of convergence patterns by providing a unique systematic comparison of energy- and labour-productivity convergence at a detailed sectoral level for 14 OECD countries, covering the period 1970–1997. A σ-convergence analysis revealed that the development of the cross-country variation in energy- and labour-productivity performance depends on the level of aggregation, with different patterns of productivity convergence and divergence across sectors. At the macroeconomic level we found evidence for energy-productivity divergence, driven by aggregate Manufacturing, as well as labour-productivity convergence, mainly driven by Services. The Manufacturing energy-productivity divergence turns out to be caused by the Iron and Steel and the Non-Ferrous Metals sectors. Moreover, despite a lack of evidence of labour-productivity convergence at the aggregate Manufacturing level, there is evidence of labour-productivity convergence in several Manufacturing sub-sectors, with Machinery as the most important exception in that it shows a clear pattern of divergence (in particular after 1985).

A β-convergence analysis, using a panel-data approach, led to the conclusion that in most sectors energy-productivity growth is relatively high in countries with relatively low initial productivity levels, while in several sectors this is also true for labour productivity. This result supports the hypothesis that relatively backward countries tend to catch-up to more advances economies, in particular in terms of energy productivity, possibly because they can benefit from the experience and technologies developed by the countries operating at the forefront.

However, in spite of the evidence of convergence, cross-country differences in energy- and labour-productivity performance seem to be persistent. Our β-convergence analysis has shown convergence to be conditional on cross-country differences in steady-state characteristics. This is in line with the results of our σ-convergence analysis, which indicated that cross-country differences in productivity levels persist, even in those sectors that display a convergence pattern. Moreover, we found that the speed of energy-productivity convergence is in general higher than the speed of labour-productivity convergence. Nevertheless, at the same time cross-country differences in energy-productivity levels were found to be still substantially larger than cross-country differences in labour-productivity levels at all levels of sectoral aggregation.

In our search for the country- and sector-specific fundamentals determining these (differences in) energy- and labour-productivity developments, we found energy prices to stimulate energy-productivity growth in the energy-intensive sectors and we also found a positive relationship between wages and labour-productivity growth in most sectors. However, our data show the cross-country differences in wages to be considerably larger than cross-country differences in final energy prices (measured by the standard deviation of the log of each variable). Hence, they are not likely to explain the persistent relatively high cross-country differences in energy-productivity levels as compared to labour-productivity levels. In addition, we found specialization and economies of scale to contribute to energy- and labour-productivity growth in several sectors, while the investment share and openness play only a very limited role in explaining (cross-country) differences in energy- and labour-productivity growth. These results imply a need for additional research to further explain sectoral trends in energy- and labour-productivity growth across countries.

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Notes

1. The paper by Miketa and Mulder (M&M) follows the same approach as we develop in this paper, and builds upon the working paper version of this paper (Mulder and de Groot 2003b). The two papers differ in important respects. Apart from studying the manufacturing sector as is done in M&M, in this paper we also consider developments in agriculture, services, transport and a macroeconomic aggregate, allowing us to control for aggregation bias. Second, we simultaneously look at energy- and labour productivity. Third, whereas M&M include developing countries in their analysis, we focus on the OECD, allowing for a more detailed analysis with better-quality data. It enables us to show that even for a relatively homogenous group of countries, substantial cross-country differences exist. Finally, on a more technical note and in contrast to M&M, this paper employs sector-specific energy-price data, it considers more control variables in the conditional convergence analysis, and it employs PPP's instead of market exhange rates (as in M&M) to convert monetary variables into a common currency, which is clearly preferable for a convergence analysis.
2. Although Dollar and Wolff (1988, 1993) distinguish 28 sectors, they only present a labour-productivity convergence indicator for a few years and did not perform a regression analysis to test for convergence patterns.

3. An in-depth discussion of this literature is beyond the scope of this paper. For good surveys we refer to Abreu et al. (2005), Barro and Sala-i-Martin (1995), Broadberry (1996), Durlauf and Quah (1999), Fagerberg (1994), Economic Journal (1996) and Islam (2003).
4. Exploratory data analysis also does not provide much evidence for the existence of an 'Energy-intensity Kuznets Curve', with a period of increasing energy intensity preceding decreasing energy-intensity levels as countries get richer. See also Berndt (1978) for a review of long-term analysis of energy-productivity trends in the US, concluding that the (scarce) historical evidence of increasing energy intensity in the US in the period before 1910 is mainly attributable to limited data quality.
5. Based on information from the IEA Energy Balances (2001), one can analyze the cross-country dispersion of the share in total final energy consumption of the various energy types across the OECD countries (measured by the standard deviation of the log of these shares). Our own analysis reveals a clear trend towards decreasing cross-country variation in the use of the four main energy types (whereby natural gas and electricity are increasingly substituted for coal and oil). Hence, one might indeed expect this increasing homogeneity in energy mix to be an important source of cross-country energy productivity convergence within the OECD. Details of this analysis are available upon request.
6. Obviously, σ-convergence and β-convergence are closely related. A narrowing dispersion of cross-country productivity differences implies that countries with a relatively poor initial productivity performance tend to grow relatively fast. However, as has been argued by Quah (1993), a statistically significant inverse relationship between the initial *level* and the *growth rate* of productivity performance can be consistent with constant or even increasing cross-country productivity differences – a phenomenon known as Galton's Fallacy of regression towards the mean. We refer to Bernard and Durlauf (1996) and Durlauf and Quah (1999) for further discussion of empirical methodological issues of convergence tests.
7. For a detailed description of the dataset, we refer to an Annex to this paper that can be downloaded from http://www.henridegroot.net/pdf/annex_isdbe.pdf. The dataset can be downloaded as an EXCEL file from http://www.henridegroot.net/pdf/isdbe_dataset.xls.
8. In the literature on convergence analysis, two measures for σ-convergence are used interchangeably: (1) the standard deviation of the log of per capita income or productivity and (2) the coefficient of variation which equals the standard deviation of per capita income or productivity divided by the sample average. We have used both measures in our convergence analysis, finding both measures to yield an identical pattern of convergence, although with small differences in the size of cross-country variance. Details are available upon request. Here, we only present the result of the first measure.
9. Excluding Finland and Italy from the sample for Services reduces the cross-country dispersion by about 40% while leaving the pattern of σ-convergence unchanged.
10. We have also tested for unconditional convergence estimating a pooled Ordinary Least Squeres Model, but all tests that we have performed clearly point at the relevance of conditional convergence. Details can be found in the Annex to this paper.
11. From the empirical macroeconomic growth literature – as briefly discussed in Section 2 – it is known that persistent differences in, for example, the technology level and institutions are an important factor in understanding cross-country differences in productivity and economic growth. Hence, any permanent unobserved factors would necessarily be correlated with the initial level of, respectively, energy- and labour productivity (y_{t-1}).
12. In his model, the individual country effect is assumed to be a linear function of the mean of the explanatory variables and a random country-specific effect, which is again assumed

to be a random variable with mean zero and constant variance. As a result this formulation minimizes the bias induced by the correlation between individual effects and explanatory variables in a random-effects model – sometimes referred to as the heterogeneity bias (Chamberlain 1982). For space constraints, the results of this model are not reported in the main text. They can be found in the Annex to this paper.

13. The regression results as shown Tables III and IV are based on an unbalanced panel, due to differences in data availability of the various variables per sector. For each sector we also list the number of observations and countries included in the regression. We have tested for the robustness of the presented β-convergence estimates by repeating the analysis for a balanced panel. This additional exercise showed that the exact results as reported in Tables III–V do change only slightly while the overall pattern of convergence and main conclusions still hold. Details are available upon request.
14. Approximating around the steady state, the convergence speed is given by $d\,\log(y_t)/dt = \lambda[\log(y^*) - \log(y_t)]$. Rewriting yields $\log(y_t) - \log(y_0) = (1 - e^{-\lambda t})[\log(y^*) - \log(y_0)]$ where (y_0) is the energy- or labour-productivity level at some initial date. From this equation we can derive that the half life (H) should satisfy the equality $e^{-\lambda H} = 0.5$, so $H = \ln(2)/\lambda$.
15. We also controlled for different specifications of energy prices (current prices, 5-year moving average, and log 3-year and log 5-year moving average), investment share $((I/Y)_{t-1}$, (I/K), $(I/K)_{t-1}$ and $\ln(I/K)_{t-1})$, as well as an interaction term of investment share and log initial energy productivity ($\ln(Y/E)_0 * (I/Y))$. All these specifications did not substantially alter the estimates. Details are available upon request.
16. For labour productivity we also controlled for different specifications of the explanatory variables, including wages (current wage, 5-year moving average, and log 3-year and log 5-year moving average), investment share $((I/Y)_{t-1}$, (I/K), $(I/K)_{t-1}$ and $\ln(I/K)_{t-1})$, as well as an interaction term of investment share and log initial labour productivity $(\ln(Y/E)_0 * (I/Y))$. All these specifications again did not substantially alter the estimates.

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